CHAPTER 2

DRAINED INLAND ORGANIC SOILS

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2.1 INTRODUCTION

Organic soils are defined in Annex 3A.5, Chapter 3, Volume 4 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and Section 1.2, Chapter 1 of this *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement)*. The guidance in this Chapter applies to all inland organic soils that have been drained, i.e. drainage of lands that started in the past and that still persists, or newly drained lands within the reporting period. This means that the water table level is at least temporarily below natural levels. Natural levels mean that the mean annual water table is near the soil surface but can experience seasonal fluctuations. Within each land-use category, water table level is manipulated to varying degrees depending on land-use purpose, e.g. for cultivating cereals, rice or for aquaculture, which can be reflected by different drainage classes.

This Chapter deals with inland organic soils that do not meet the definition of “coastal” given in Chapter 4 of this *Wetlands Supplement*. In this Chapter, the term “organic soils” refers to “inland organic soils” in this Chapter.

This Chapter provides supplementary guidance on estimating greenhouse gas emissions and removals from drained inland organic soils in the following land-use categories, as defined in Volume 4 of the *2006 IPCC Guidelines*: Chapter 4 (Forest Land), Chapter 5 (Cropland), Chapter 6 (Grassland), Chapter 7 (Wetlands), Chapter 8 (Settlements) and Chapter 9 (Other Land). Managed coastal organic soils are covered in Chapter 4 of this *Wetlands Supplement*. Rewetted organic soils are considered in Chapter 3 of this *Wetlands Supplement*.

This Chapter clarifies Volume 4 of the *2006 IPCC Guidelines* by summarising all emission factors and harmonising methods for organic soils across all land-use types. On the basis of recent advances in scientific information, this Chapter also updates, improves and completes methodologies and emission factors for greenhouse gas emissions and removals in the *2006 IPCC Guidelines* and fills gaps where new scientific knowledge allows implementation of robust methodologies and use of better emission factors at the Tier 1 level.

This Chapter updates the *2006 IPCC Guidelines* for:

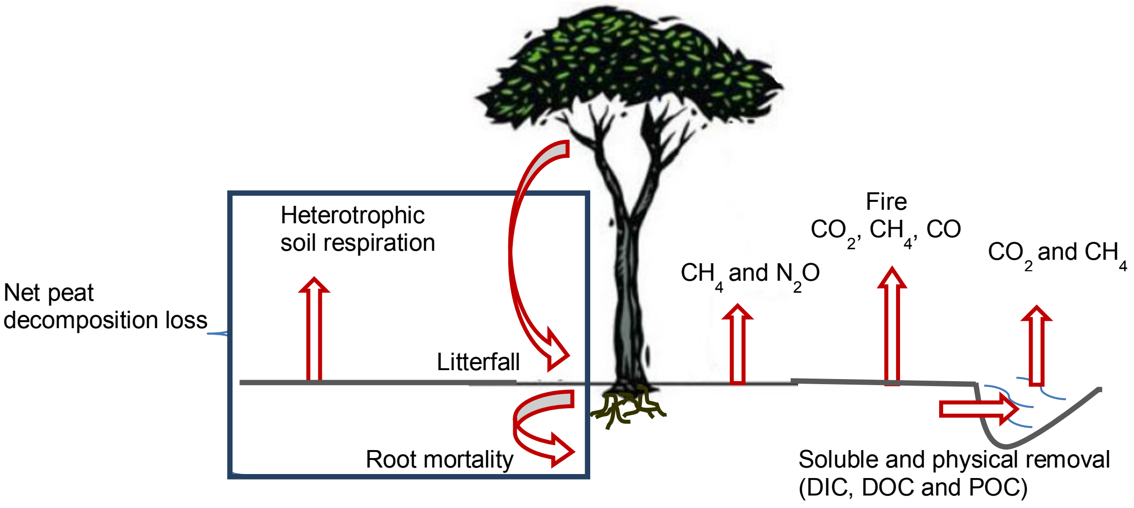
- carbon dioxide (CO_2) emissions and removals from drained organic soils (referring to Chapters 4 to 9, Volume 4, *2006 IPCC Guidelines*);
- methane (CH_4) emissions from drained organic soils (referring to Chapter 7, Volume 4, *2006 IPCC Guidelines*); and
- nitrous oxide (N_2O) emissions from drained organic soils (referring to Chapter 11, Volume 4, *2006 IPCC Guidelines*).

This Chapter gives new guidance not contained in the *2006 IPCC Guidelines* by:

- providing methodologies and emission factors for CH_4 emissions from drainage ditches (referring to Chapters 4 to 9, Volume 4, *2006 IPCC Guidelines*);
- providing methodologies and emission factors for off-site CO_2 emissions associated with dissolved organic carbon (DOC) release from organic soils to drainage waters (referring to Chapters 4 to 9, Volume 4, *2006 IPCC Guidelines*);
- providing methodologies and emission factors for CO_2, CH_4 and carbon monoxide (CO) emissions from peat fires.

This Chapter also contains an Appendix that provides the basis for future methodological development for estimating CO_2 emissions associated with other forms of waterborne carbon loss, specifically particulate organic carbon (POC) and dissolved inorganic carbon (DIC) (referring to Chapters 4 to 9, Volume 4, *2006 IPCC Guidelines*). All fluxes are summarised in Figure 2.1.

Figure 2.1 **Summary of fluxes from drained organic soils**



2.2 LAND REMAINING IN A LAND-USE CATEGORY

The *2006 IPCC Guidelines* provide guidance for carbon stock changes in five carbon pools, namely above-ground and below-ground biomass, dead wood, litter and soil for managed land on organic soils. This Chapter updates the *2006 IPCC Guidelines* for the soil organic carbon pool in organic soils.

2.2.1 CO_2 emissions and removals from drained inland organic soils

This section deals with the impacts of drainage and management on CO_2 emissions and removals from organic soils due to organic matter decomposition and loss of DOC in drainage waters. DOC losses lead to off-site CO_2 emissions. There are also erosional losses of POC, as well as waterborne transport of DIC (primarily dissolved CO_2) derived from autotrophic and heterotrophic respiration within the organic soil. At present, the science and available data are insufficient to provide guidance on CO_2 emissions or removals associated with these waterborne carbon fluxes; Appendix 2a.1 provides a basis for future methodological development in this area. General information and guidance for estimating changes in soil carbon stocks are provided in Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*; this should be read before proceeding with the guidance provided here. This guidance is based on the observation that in drained organic soils, emissions persist as long as the soil remains drained or as long as organic matter remains (Wösten *et al*., 1997; Deverel & Leighton, 2010).

Equation 2.3 in Chapter 2, Volume 4 of the *2006 IPCC Guidelines* refers to annual carbon stock changes for a stratum of a land-use category as a sum of changes in all pools. This section addresses the stratum of a land-use category on drained organic soils. The equation is repeated here as Equation 2.1 to demonstrate how the guidance in this *Wetlands Supplement* links to the *2006 IPCC Guidelines*.

EQUATION 2.1
ANNUAL CARBON STOCK CHANGES FOR A STRATUM OF A LAND-USE CATEGORY AS A SUM OF CHANGES IN ALL POOLS
(EQUATION 2.3 IN CHAPTER 2, VOLUME 4, *2006 IPCC GUIDELINES*)

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

Where:

ΔC_{LU_i} = carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB = above-ground biomass

BB = below-ground biomass

DW = dead wood

LI = litter

SO = soils

HWP = harvested wood products

Guidance for the carbon pools above-ground biomass, below-ground biomass, dead wood, litter and harvested wood products in the *2006 IPCC Guidelines* is not dealt with further in these guidelines.

This section of the *Wetlands Supplement* updates and complements the guidance on the drained organic soils component of ΔC_{SO}, referred to as $L_{organic}$ in Equation 2.24, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*. For transparent distinction between drained and rewetted organic soils, the term is further specified as CO_2-$C_{organic, drained}$ in Equation 2.2. CO_2-$C_{organic, drained}$ consists of on-site CO_2 emissions/removals of the organic soil from mineralisation and sequestration processes (CO_2-$C_{on-site}$), off-site CO_2 emissions from leached carbon from the organic soil (CO_2-C_{DOC}) and anthropogenic peat fires (L_{fire}). Countries are encouraged to consider POC when using higher tier methodologies (see Appendix 2a.1). CO_2 emissions from peat fires are not explicitly addressed in Equation 2.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*, but can be important on drained organic soils. CO_2 emissions from peat fires are therefore included in Equation 2.2 as L_{fire} (Section 2.2.2.3).

EQUATION 2.2

CO_2-C EMISSIONS/REMOVALS BY DRAINED ORGANIC SOILS

$$CO_2 - C_{organic,drained} = CO_2 - C_{on-site} + CO_2 - C_{DOC} + L_{fire} - CO_2 - C$$

Where:

CO_2-$C_{organic, drained}$ = CO_2-C emissions/removals by drained organic soils, tonnes C yr^{-1}

CO_2-$C_{on-site}$ = on-site CO_2-C emissions/removals by drained organic soils, tonnes C yr^{-1}

CO_2-C_{DOC} = CO_2-C emissions from dissolved organic carbon exported from drained organic soils, tonnes C yr^{-1}

L_{fire}-CO_2-C = CO_2-C emissions from burning of drained organic soils, tonnes C yr^{-1}

2.2.1.1 ON-SITE CO_2 EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS (CO_2-$C_{ON-SITE}$)

This section gives supplementary guidance for CO_2 emissions and removals from drained organic soils in all land-use categories as defined in Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*. The IPCC land-use categories are discussed in Chapter 4 (Forest Land), Chapter 5 (Cropland), Chapter 6 (Grassland), Chapter 7 (Wetlands), Chapter 8 (Settlements) and Chapter 9 (Other Land). Flooded Lands (Chapter 7) are not included in this *Wetlands Supplement*.

Guidance is given for CO_2 emissions from the soil carbon pool in drained organic soils in line with Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*. Guidance for changes in the carbon pools in above-ground and below-ground biomass, dead wood and litter on these lands is provided in the *2006 IPCC Guidelines* and remains unchanged.

CHOICE OF METHOD

The most important factors considered for estimating on-site CO_2 emissions and removals from drained organic soils are land use and climate. Other factors such as nutrient status (or fertility) of the soil and drainage level affect emissions and can be considered where appropriate and with higher tier methods. It is *good practice* to stratify land-use categories by climate domain (Table 4.1, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*), nutrient status (*Good Practice Guidance for Land Use, Land-Use Change and Forestry* (*GPG-LULUCF*) and Section 7.2.1.1, Chapter 7, Volume 4 of the *2006 IPCC Guidelines*) and drainage class (shallow or deep) according to the stratification given in Table 2.1.

Nutrient status is defined in the *GPG-LULUCF* and the *2006 IPCC Guidelines* (Section 7.2.1.1, Chapter 7, Volume 4). Generally, ombrogenic organic soils are characterised as nutrient-poor, while minerogenic organic soils are characterised as nutrient-rich. This broad characterisation may vary by peatland type or national circumstances.

Drainage class is defined as the mean annual water table averaged over a period of several years; the shallow-drained class is defined as the mean annual water table depth of less than 30 cm below the surface; the deep-drained class is defined as the mean annual water table depth of 30 cm and deeper below the surface.

For Tier 1 methods, if the typical range of mean annual water table levels of drained organic soils for each land-use category is unknown - water table depth is specific for land-use categories and climate domains - the default assumption is that the organic soil is deep-drained because deep-drained conditions are the most widespread and suitable for a wide range of management intensities. Higher tier methods could further differentiate the drainage intensity within land-use categories if there are significant areas that differ from the default deep-drained conditions.

Figure 2.5 in Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines* provides a decision tree for identification of the appropriate tier to estimate CO_2 emissions from drained organic soils by land-use category.

Tier 1

The basic methodology for estimating annual carbon loss from drained organic soils is presented in Section 2.3.3 and Equation 2.26 in Volume 4 of the *2006 IPCC Guidelines*, as further specified in Equation 2.2. Equation 2.3 refers to CO_2-$C_{on\text{-}site}$ in Equation 2.2 with stratification of land-use categories by climate domain and nutrient status. Nutrient status and drainage classes only need to be differentiated for those land-use categories and climate domains for which emission factors are differentiated in Table 2.1.

At Tier 1, there is no differentiation between CO_2 emissions from long-term drained organic soils and organic soils after initial drainage or where drainage is deepened. High carbon loss from drained organic soils can occur immediately after initial drainage of organic soils (Stephens *et al.*, 1984; Wösten *et al.*, 1997; Hooijer *et al.*, 2012) even if land use does not change. These CO_2-$C_{on\text{-}site}$ emissions in the transitional phase are not captured by the Tier 1 default emission factors shown in Table 2.1, which were derived from data representing long-term land uses present for decades in the boreal and temperate climate zones, and land uses drained for more than six years in the tropical climate zone. A transitional phase is thus not captured by Tier 1 methodology due to lack of data for deriving default emission factors. After initial drainage of organic soils and if a transitional phase occurs, this should be addressed by higher tier methods.

EQUATION 2.3
ANNUAL ON-SITE CO_2-C EMISSIONS/REMOVALS FROM DRAINED ORGANIC SOILS EXCLUDING EMISSIONS FROM FIRES

$$CO_2-C_{on-site} = \sum_{c,n,d} \left(A \bullet EF\right)_{c,n,d}$$

Where:

CO_2-$C_{on\text{-}site}$ = annual on-site CO_2-C emissions/removals from drained organic soils in a land-use category, tonnes C yr^{-1}

A = land area of drained organic soils in a land-use category in climate domain c, nutrient status n and drainage class d, ha

EF = emission factors for drained organic soils, by climate domain c, nutrient status n and drainage class d, tonnes C $ha^{-1}yr^{-1}$

Tier 2

The Tier 2 approach for CO_2 emissions/removals from drained organic soils incorporates country-specific information into Equations 2.2 and 2.3 to estimate CO_2 emissions/removals. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Improvements to the Tier 1 approach may include: 1) a derivation of country-specific emission factors; 2) specification of climate sub-domains considered suitable for refinement of emission factors; 3) a finer, more detailed classification of management systems with a differentiation of land-use intensity classes; 4) a differentiation by drainage classes; 5) differentiation of emission factors by time since drainage or the time since changes in drainage class, e.g. between emission factors reflecting additional emissions after deepening of drainage or new drainage and long-term stable water tables, or 6) a finer, more detailed classification of nutrient status, e.g. by nitrogen, phosphorus or pH.

It is *good practice* to derive country-specific emission factors if measurements representing the national circumstances are available. Countries need to document that methodologies and measurement techniques are compatible with the scientific background for Tier 1 emission factors in Annex 2A.1. Moreover, it is *good practice* for countries to use a finer classification for climate and management systems, in particular for drainage classes, if there are significant differences in measured carbon loss rates among these classes. Note that any country-specific emission factor must be accompanied by sufficient national or regional land-use/management activity and environmental data to represent the appropriate climate sub-domains and management systems for the spatial domain for which the country-specific emission factor is applied.

The general guidance provided in Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines* also applies here.

Tier 3

CO_2 emissions/removals from drained organic soils can be estimated using modelling and/or measurement approaches. Dynamic, mechanistic models will typically be used to simulate underlying processes while capturing the influence of land use and management, particularly the effect of seasonally variable levels of drainage on decomposition (van Huissteden *et al*., 2006). General considerations for organic soils given in Section 2.3.3, Chapter 2, Volume 4 of the *2006 IPCC Guidelines* also apply here. It is *good practice* to describe methodologies and models transparently, to document considerations for the choice and application of the model in the inventory, and to provide evidence that this represents the national circumstances according to the guidance in Section 2.5, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

All Tier 1 emission factors have been updated from the *2006 IPCC Guidelines* based on a large number of new measurement data from all land-use categories and climate zones. This new evidence allows for stratification of more land-use categories and climate domains by nutrient status than in the *2006 IPCC Guidelines*. In addition, temperate, nutrient-rich Grassland is further stratified into shallow-drained (less than approximately 30 cm below the surface) and deep-drained. Within each land-use category, drained organic soils can experience a wide range of mean annual water table levels that depend upon regional climatic characteristics and specific land-use activity or intensity. Emission factors for temperate Grassland are given for shallow-drained and deep-drained soils. Shallow-drained and deep-drained Grassland emission factors differ significantly. In the absence of additional national information about mean annual water table and/or land-use intensity as a proxy, countries should choose deep-drained factors as default.

The *GPG-LULUCF* and the *2006 IPCC Guidelines* (Section 7.2.1.1, Chapter 7, Volume 4) distinguish between nutrient-rich and nutrient-poor organic soils in some land-use categories and climate zones. This approach is maintained here, in line with the guidance given in the *2006 IPCC Guidelines*. Two alternative emission/removal factors are given in Table 2.1 for boreal nutrient-poor Forest Land; countries need to choose the one that matches their national land-use definition.

Default Tier 1 emission/removal factors for drained organic soils (Table 2.1) were generated using a combination of subsidence and flux data found in the literature, as described in Annex 2A.1. CO_2-C losses occur predominantly in the drained, oxic soil layer and thus reflect human-induced CO_2-C fluxes. The part of the soil profile affected by drainage can be deeper or shallower than the default 0 to 30 cm layer considered in the Tier 1 default methodology for soil organic carbon (SOC) pools in mineral soils.

TABLE 2.1
TIER 1 CO_2 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES[a]

Land-use category		**Climate / vegetation zone**	**Emission factor[a] (tonnes CO_2-C $\text{ha}^{-1}\text{yr}^{-1}$)**	**95% Confidence interval[b]**		**No. of sites**	**Citations/comments**
Forest Land, drained, including shrubland and drained land that may not be classified as forest[c]	Nutrient-poor	Boreal	0.37	-0.11	0.84	63	Lohila *et al*., 2011; Minkkinen & Laine, 1998; Minkkinen *et al*., 1999; Ojanen *et al*., 2010, 2013; Simola *et al*., 2012
Forest Land, drained[d]	Nutrient-poor	Boreal	0.25	-0.23	0.73	59	Lohila *et al*., 2011; Minkkinen & Laine, 1998; Minkkinen *et al*., 1999; Ojanen *et al*., 2010, 2013; Simola *et al*., 2012
	Nutrient-rich	Boreal	0.93	0.54	1.3	62	Laurila *et al*., 2007; Lohila *et al*., 2007; Minkkinen & Laine, 1998; Minkkinen *et al*., 1999, 2007*b*; Ojanen *et al*., 2010, 2013; Simola *et al*., 2012
Forest Land, drained		Temperate	2.6	2.0	3.3	8	Glenn *et al*., 1993; Minkkinen *et al*., 2007*b*; von Arnold *et al*., 2005*a*, *b*; Yamulki *et al*., 2013
Forest Land and cleared Forest Land (shrubland[e]), drained		Tropical	5.3	-0.7	9.5	21	Ali *et al*., 2006; Brady, 1997; Chimner & Ewel, 2005; Comeau *et al*., 2013; Dariah *et al*., 2013; Darung *et al*., 2005; Furukawa *et al*., 2005; Hadi *et al*., 2005; Harrison *et al*., 2007; Hergoualc'h & Verchot, 2011; Hertel *et al*., 2009; Hirano *et al*., 2009, 2012; Inubushi *et al*., 2003; Ishida *et al*., 2001; Jauhiainen *et al*., 2008, 2012a; Melling *et al*., 2005a, 2007a; Rahaoje *et al*., 2000; Shimamura & Momose, 2005; Sulistiyanto, 2004; Sundari *et al*., 2012

TABLE 2.1 (CONTINUED)
TIER 1 CO_2 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES [a]

Land-use category	Climate / vegetation zone	Emission factor[a] (tonnes CO_2-C $ha^{-1}yr^{-1}$)	95% Confidence interval[b]		No. of sites	Citations/comments
Plantations, drained, unknown or long rotations[f]	Tropical	15	10	21	n.a.	Average of emission factors for acacia and oil palm
Plantations, drained, short rotations, e.g. acacia[f], [g]	Tropical	20	16	24	13	Basuki *et al*., 2012; Hooijer *et al*., 2012; Jauhiainen *et al*., 2012*a*; Nouvellon *et al*., 2012; Warren *et al*., 2012
Plantations, drained, oil palm[f]	Tropical	11	5.6	17	10	Comeau *et al*., 2013; Couwenberg & Hooijer, 2013; Dariah *et al*., 2013; DID & LAWOO, 1996; Henson & Dolmat, 2003; Hooijer *et al*., 2012; Lamade & Bouillet, 2005; Marwanto & Agus, 2013; Melling *et al*., 2005*a*, 2007*a*, 2013; Warren *et al*., 2012
Plantations, shallow-drained (typically less than 0.3 m), typically used for agriculture, e.g. sago palm[f]	Tropical	1.5	-2.3	5.4	5	Dariah *et al*., 2013; Hairiah *et al*., 1999; Ishida *et al*., 2001; Lamade & Bouillet, 2005; Matthews *et al*., 2000; Melling *et al*., 2005*a*, 2007*a*; Watanabe *et al*., 2009
Cropland, drained	Boreal and Temperate	7.9	6.5	9.4	39	Drösler *et al*., 2013; Elsgaard *et al*., 2012; Grønlund *et al*., 2008; Kasimir-Klemedtsson *et al*., 1997; Leifeld *et al*., 2011; Maljanen *et al*., 2001*a*, 2003*a*, 2004, 2007; Morrison *et al*., 2013; Petersen *et al*., 2012

TABLE 2.1 (CONTINUED)
TIER 1 CO_2 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES [a]

Land-use category	**Climate / vegetation zone**	**Emission factor[a] (tonnes CO_2-C ha^{-1}yr^{-1})**	**95% Confidence interval[b]**		**No. of sites**	**Citations/comments**
Cropland and fallow, drained	Tropical	14	6.6	26	10	Ali *et al*., 2006; Chimner, 2004; Chimner & Ewel, 2004; Dariah *et al*., 2013; Darung *et al*., 2005; Furukawa *et al*., 2005; Gill & Jackson, 2000; Hairiah *et al*., 2000; Hirano *et al*., 2009; Ishida *et al*., 2001; Jauhiainen *et al*., 2012*a*; Melling *et al*., 2007*a*
Cropland, drained, paddy rice	Tropical	9.4	-0.2	20	6	Dariah *et al*., 2013; Furukawa *et al*., 2005; Hadi *et al*., 2005; Hairiah *et al*., 1999; Inubushi *et al*., 2003; Ishida *et al*., 2001; Matthews *et al*., 2000; Melling *et al*., 2007*a*
Grassland, drained	Boreal	5.7	2.9	8.6	8	Grønlund *et al*., 2006; Kreshtapova & Maslov, 2004; Lohila *et al*., 2004; Maljanen *et al*., 2001*a*, 2004; Nykänen *et al*., 1995; Shurpali *et al*., 2009
Grassland, drained, nutrient-poor	Temperate	5.3	3.7	6.9	7	Drösler *et al*., 2013; Kuntze, 1992
Grassland, deep-drained, nutrient-rich	Temperate	6.1	5.0	7.3	39	Augustin, 2003; Augustin *et al*., 1996; Czaplak & Dembek, 2000; Drösler *et al*., 2013; Elsgaard *et al*., 2012; Höper, 2002; Jacobs *et al*., 2003; Kasimir-Klemedtsson *et al*., 1997; Langeveld *et al*., 1997; Leifeld *et al*., 2011; Lorenz *et al*., 1992; Meyer *et al*., 2001; Nieveen *et al*., 2005; Okruszko, 1989; Schothorst, 1977; Schrier-Uijl *et al*., 2010*a*, *c*; Veenendaal *et al*., 2007; Weinzierl, 1997

TABLE 2.1 (CONTINUED)
TIER 1 CO_2 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES [a]

Land-use category	Climate / vegetation zone	Emission factor[a] (tonnes CO_2-C $ha^{-1}yr^{-1}$)	95% Confidence interval[b]		No. of sites	Citations/comments
Grassland, shallow-drained, nutrient-rich	Temperate	3.6	1.8	5.4	13	Drösler *et al.*, 2013; Jacobs *et al.*, 2003; Lloyd, 2006
Grassland, drained	Tropical	9.6	4.5	17	n.a.	Updated from Table 6.3, Chapter 6, Volume 4, *2006 IPCC Guidelines*[h]
Peatland Managed for Extraction[i]	Boreal and Temperate	2.8	1.1	4.2	20	Ahlholm & Silvola, 1990; Glatzel *et al.*, 2003; McNeil & Waddington, 2003; Shurpali *et al.*, 2008; Strack & Zuback, 2013; Sundh *et al.*, 2000; Tuittila & Komulainen, 1995; Tuittila *et al.*, 2000, 2004; Waddington *et al.*, 2010
Peatland Managed for Extraction[i]	Tropical	2.0	0.06	7.0	n.a.	Table 7.4, Chapter 7, Volume 4, *2006 IPCC Guidelines*
Settlements	All climate zones	There is no fixed default emission/removal factor for Settlements. For this category, it is *good practice* to take the default emission/removal factor from Table 2.1 of the land-use category that is closest to national conditions of drained organic soils under Settlements. Information about national conditions could include drainage level, vegetation cover, or other management activities. For example, drained organic soils in urban green areas, parks or gardens could use the default Tier 1 emission/removal factor for Grassland, deep-drained given in Table 2.1.				
Other Land	All climate zones	*Other Land Remaining Other Land*: 0 *Land Converted to Other Land*: maintain emission factor of previous land-use category				

[a] Mean

[b] Some confidence intervals contain negative values. These were mathematically calculated based on error propagation of uncertainties. However, all underlying CO_2 fluxes were positive.

[c] Forest broader than FAO definition

[d] Forest according to FAO definition

[e] Shrubland refers to any type of land sparsely or fully covered with shrubs or trees that may fulfil the national forest definition. It extends to degraded lands that cannot be clearly classified as forest or non-forest.

[f] Plantations are reported under land-use categories according to national land-use definitions.

[g] Number derived solely from Acacia plantation data

[h] The emission factor for Cropland for tropical zone was multiplied by the ratio between the emission factors for Grassland, drained, nutrient-poor and Cropland for temperate zone; the same applies to the confidence interval. This new ratio updates the ratio applied to derive the emission factor for Grassland in the tropical zone in Table 6.3, Chapter 6, Volume 4, *2006 IPCC Guidelines*.

[i] On-site CO_2-C emissions from drained peat deposits only. For off-site CO_2-C emissions from peat extracted for horticultural or energy use, see Chapter 7, Volume 4, *2006 IPCC Guidelines*.

Common tropical plantations include oil palm, sago and *Acacia crassicarpa*. In Table 2.1, plantations are not allocated to a specific land-use category. It is *good practice* to report plantations in the appropriate national land-use category according to national land-use definitions. National land-use definitions commonly classify timber and fibre plantations as Forest Land and oil palm or sago palm plantations as Cropland.

Tier 2

The Tier 2 approach for carbon loss from drained organic soils incorporates country-specific information into Equation 2.2 to estimate emissions. Tier 2 also uses the same procedural steps for calculations as provided for Tier 1. Tier 2 emission factors by land-use category can, in general, be developed depending on a) climate, b) drainage layout and intensity, c) nutrient status and, d) land-use intensity and practices.

Tier 2 emission factors could include the following refinements:

- use of country-specific emission factors measured or calculated locally taking into account climatic factors that provide for wetter or drier drainage classes than those defined here;
- use of country-specific emission factors measured or calculated locally taking into account slope factors (e.g. blanket bogs) that may promote wetter or drier drainage classes than those defined here;
- derivation of emission factors for boreal Forest Land by nutrient status (rich/poor) if the two emission factors are significantly different (see Table 2.1);
- development of boreal and temperate Grassland emission factors according to land-use intensity, e.g. to distinguish high-intensity (fertilised, ploughed and reseeded) Grassland from low-intensity permanent Grassland, or from moorland rough grazing (grazing by hardier breeds of sheep) on drained blanket bogs; and
- integration of temporal dynamics associated with changes in decomposition rates that may be related to drainage, management or to the physical and chemical changes to peat over time, including a possible transition period of high emissions associated with drainage or deepening of drainage in lands remaining in a land-use category.

CO_2 measurements derived through methods described in Annex 2A.1 and disaggregated by management practices should be used to develop more precise, locally appropriate emission factors. CO_2 flux measurements do not take account of waterborne carbon losses, which must therefore be considered separately. In contrast, subsidence-based measurements effectively incorporate waterborne carbon losses into the estimated stock change. This methodological difference has to be considered when developing higher tier methods in order to avoid double-counting.

Tier 3

A Tier 3 approach allows for a variety of methods and may use measurements or process-based models or other more elaborate approaches, adequately validated using observation data that take into account temporal and spatial variations. Tier 3 should involve a comprehensive understanding and representation of the dynamics of CO_2 emissions and removals from drained organic soils, including the effects of management practices, site characteristics, peat type and depth and drainage depth, among other factors. Tier 3 approaches could start by developing relationships between drainage or nutrient status and heterotrophic CO_2 emissions, which can be further refined by land-use category and fertilisation. Furthermore, organic soils in Forest Land undergo a cycle related to rotation of the tree cohorts and carbon losses associated with harvesting and site preparation should be accounted for. Models could describe the rotational variation in water tables.

When peat is extracted, the peatland surface is disturbed by machinery and may be fertilised afterwards or otherwise amended for regeneration. Moreover, drainage systems may be renewed and dredging of ditches may cause disturbances that alter greenhouse gas emissions and removals. These measures result in emission/removal rates that vary predictably over time, which may in Tier 3 methods be captured by models used. Emissions from stockpiles of drying peat are much more uncertain. Higher temperatures may cause stockpiles to release more CO_2 than the excavation field but data are at present insufficient to provide guidance. Methods for estimating this emission may be developed at Tier 3.

CHOICE OF ACTIVITY DATA

All management practices for land remaining in a land-use category are assumed to result in persistent emissions from soils as long as the management system remains in place or as long as the land falls under the definition of organic soils. Activity data consist of areas of land remaining in a land-use category on organic soils stratified by climate domain, soil nutrient status, drainage class or additional criteria such as management practices. Total areas should be determined according to the Approaches laid out in Chapter 3, Volume 4 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. The estimation of CO_2 emissions/removals from drained organic soils will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories and other biophysical data. Stratification of land-use categories according to climate domains, based on default or country-specific classifications, can be accomplished with overlays of land use on suitable climate and soil maps.

Under most circumstances, the area of organic soils will remain constant over time. However, the area of organic soils may change as organic soil disappears following drainage.

Tier 1

The Tier 1 approach requires area data on drained organic soils for each land-use category, disaggregated by appropriate climate domains, nutrient status and drainage class as applicable. Classification systems for activity data that form the basis of a Tier 1 inventory are provided in the respective land-use chapters of the *2006 IPCC Guidelines*.

Several institutions, including ISRIC and FAO, have country-specific and global maps that include organic soils (http://www.fao.org/geonetwork/srv/en/main.home or http://www.isric.org/). A global consortium has been formed to make a new fine resolution digital soil map of the world (http://www.globalsoilmap.net/).

The *GPG-LULUCF* and the *2006 IPCC Guidelines* (Section 7.2.1.1, Chapter 7, Volume 4) distinguish between nutrient-rich and nutrient-poor organic soils in some land-use categories and climate zones. This approach is maintained here, in line with guidance given in the *2006 IPCC Guidelines*. Nutrient-poor organic soils predominate in boreal regions, while in temperate regions nutrient-rich organic soils are more common. It is *good practice* for boreal countries that do not have information on areas of nutrient-rich and nutrient-poor organic soils to use the emission factor for nutrient-poor organic soils. It is *good practice* for temperate countries that do not have such data to use the emission factor for nutrient-rich organic soils. Only one default factor is provided for tropical regions, and disaggregation by soil fertility is therefore not necessary in the tropical climate zone when using the Tier 1 method. Due to lack of data, rice fields on tropical organic soils are not disaggregated by water management regimes.

Areas of shallow-drained and deep-drained organic soils with Grasslands need to be derived from national data. Data from water management plans, such as target water table levels, can serve as a source of information. Land-use intensity, e.g. the time of the first cut of Grassland, grazing intensity, or animal production levels, can serve as a proxy, as can restrictions imposed by water management or biodiversity management (e.g. riparian zones, buffer zones, or nature conservation for species or habitats with a typical water regime).

Without additional national information about mean annual water table and/or land-use intensity as proxy, countries should choose deep-drained as the default.

Tiers 2 and 3

Activity data for higher tier estimates are generally derived following the methods presented in Chapter 3, Volume 4 of the *2006 IPCC Guidelines*. Activity data may be spatially explicit and could be disaggregated by type of management, drainage depth and/or nutrient status to improve the accuracy of the inventory if different land-management systems use different drainage depths and/or nutrient levels, and if appropriate emission factors are available. In general, practices that increase carbon stocks in mineral soils by increased organic material input (e.g. fertilisation, liming, etc.) do not have a sequestration effect in drained organic soils.

The combination of land-use databases and soil maps or spatially explicit data allows delineation of combinations of land-use categories, climate domains, drainage classes and management systems and their changes over time on organic soils. Data and their documentation could combine information from a land-use transition matrix specifically made for organic soils. Stratification needs to be consistently applied across the entire time series.

Information sources about drainage with adequate disaggregation may include:

- national land-use statistics, land-use maps and soil maps, maps of water and nature conservation zones with restrictions for water management, wetlands;
- national water management statistics: in most countries, the agricultural land base including Cropland is usually surveyed regularly, providing data on distribution of different land uses, crops, tillage practices and other aspects of management, often at sub-national regional level; these statistics may originate, in part, from remote sensing methods, from which additional information about wetness or periods with seasonal flooding could be extracted;
- inventory data from a statistically based, plot-sampling system of water table wells, ditches and surface waters on organic soils: the water table is monitored at specific permanent sample plots either continuously or on plots that are revisited on a regular basis; it has to be documented that the water data represent the water table in the organic soil and for what land use and drainage stratum and that the data cover a representative period, which represents a multi-year mean annual water table;

- water management plans and documentation from water management installations;
- drainage maps;
- maps of drainage or (partial) rewetting projects including remote sensing;

CALCULATION STEPS FOR TIER 1

The steps for estimating the direct loss of soil carbon from drained organic soils are as follows:

Step 1: Determine areas with drained organic soils under each land-use category, disaggregated by climate domain and other appropriate factors as outlined above. In the case of Tier 1 emission factors, where necessary land areas are further stratified into nutrient-rich and nutrient-poor organic soils. Temperate nutrient-rich Grassland is further stratified into shallow-drained and deep-drained classes.

Step 2: Assign the appropriate emission factor from Table 2.1 for annual losses of CO_2 to each land-use category, climate domain, nutrient status and drainage class stratum.

Step 3: Multiply each area by the appropriate emission factor using Equation 2.3.

UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exist in estimating emissions and removals in organic soils: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in the emission/removal factors for Tier 1 or 2 approaches; and 3) model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are smaller with more sampling to estimate values for land-use categories, while accuracy is more likely to be increased through implementation of higher tier methods that incorporate country-specific information.

For Tier 1, the default uncertainty level of emission/removal factors is the 95% confidence interval given in Table 2.1. Countries developing specific emission factors for their inventories at higher tiers should assess the uncertainty of these factors.

If using aggregate land-use area statistics for activity data (e.g. FAO data), the inventory compiler may have to apply a default level of uncertainty for land area estimates on organic soils (±20%; twice the uncertainty estimate given in Table 3.7 for mineral soils in the *2006 IPCC Guidelines*). It is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level of uncertainty. Uncertainties in activity data may be reduced through a better monitoring system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. Uncertainties in activity data and emission/removal factors need to be combined using an appropriate method, such as simple error propagation equations. Details are given in Chapter 3, Volume 1 of the *2006 IPCC Guidelines* and in Chapter 5 of the *GPG-LULUCF*.

Accuracy can be increased by deriving country-specific factors using a Tier 2 method or by developing a Tier 3 country-specific estimation system. The underlying basis for higher tier approaches will be measurements in the country or neighbouring regions that address the effect of land use and management on CO_2 emissions/removals from drained organic soils. In addition, uncertainties can be reduced through stratification by significant factors responsible for within-country differences in land-use and management impacts, such as variation among climate domains and/or organic soil types.

2.2.1.2 OFF-SITE CO_2 EMISSIONS VIA WATERBORNE CARBON LOSSES FROM DRAINED INLAND ORGANIC SOILS

Waterborne carbon comprises DOC, POC, the dissolved gases CO_2 and CH_4, and the dissolved carbonate species HCO_3^- and CO_3^{2-}. Particulate inorganic carbon (PIC) losses from organic soils are negligible. Collectively, waterborne carbon export can represent a major part of the overall carbon budget of an organic soil and in some cases can exceed net land-atmosphere CO_2 exchange (e.g. Billett *et al.*, 2004; Rowson *et al.*, 2010). It is therefore important that waterborne carbon be included in flux-based (i.e. gain-loss) approaches for soil carbon estimation, to avoid systematic under-estimation of soil carbon losses. Airborne (erosional) POC loss may also be significant where land use leads to bare soil exposure, but little data exist to quantify this (see Appendix 2a.1).

Different forms of waterborne carbon have different sources, behaviour and fate, and different approaches are therefore required to quantify off-site CO_2 emissions associated with each form. In most peatlands and organic soils, DOC forms the largest component of waterborne carbon export (e.g. Urban *et al.*, 1989; Dawson *et al.*, 2004; Jonsson *et al.*, 2007; Dinsmore *et al.*, 2010). DOC export can be affected by land use, in particular drainage (Wallage *et al.*, 2006; Strack *et al.*, 2008; Urbanová *et al.*, 2011; Moore *et al.*, 2013). It is reactive within aquatic ecosystems and most DOC is thought to ultimately be converted to CO_2 and emitted to the atmosphere (see Annex 2A.2 for supporting discussion). It is therefore *good practice* to include DOC export in CO_2 reporting, and a Tier 1 methodology for this purpose is described below.

Of the other forms of waterborne carbon, POC fluxes are typically very low from vegetated peatlands and organic soils, but can become very large where bare organic soil becomes exposed, e.g. due to erosion, peat extraction, burning and conversion to Cropland. Although it may be possible to estimate POC loss fluxes as a function of bare soil exposure, high uncertainty remains regarding the reactivity and fate of POC exported from organic soils. Some POC is likely to be converted to CO_2, but POC that is simply translocated from the soil profile to other stable carbon stores, such as freshwater or marine sediments, may not lead to CO_2 emissions. Due to the uncertain fate of POC export, an estimation method is not presented at this time; current knowledge and data needed to support POC estimation in future are described in Appendix 2a.1.

Gaseous CO_2 and CH_4 dissolved in water transported laterally from the organic soil matrix represent indirectly emitted components of the total emission of these gases from the land surface. Dissolved CO_2 in excess of atmospheric pressure will also be degassed from drainage waters, while some DIC may be transported downstream. At present, available data are insufficient (particularly for drained organic soils) to permit default emission factors to be derived. Additional information and future methodological requirements needed to support full accounting of emissions associated with waterborne inorganic carbon are included in Appendix 2a.1.

CHOICE OF METHOD

The basic methodology for estimating annual off-site CO_2 emissions associated with waterborne carbon loss from drained organic soils is presented in Equation 2.4:

EQUATION 2.4

ANNUAL OFF-SITE CO_2 EMISSIONS DUE TO DOC LOSS FROM DRAINED ORGANIC SOILS (CO_2)

$$CO_2{-}C_{DOC} = \sum_{c,n} \left(A \bullet EF_{DOC}\right)_{c,n}$$

Where:

CO_2-C_{DOC} = annual off-site CO_2-C emissions due to DOC loss from drained organic soils, tonnes C yr^{-1}

$A_{c,n}$ = land area of drained organic soils in a land-use category in climate zone c and nutrient status n, ha

$EF_{DOCc,n}$ = emission factors for annual CO_2 emissions due to DOC loss from drained organic soils, by climate zone c and nutrient status n, tonnes C $ha^{-1}yr^{-1}$

EF_{DOC} can be calculated from Equation 2.5:

EQUATION 2.5

EMISSION FACTOR FOR ANNUAL CO_2 EMISSIONS DUE TO DOC EXPORT FROM DRAINED ORGANIC SOILS

$$EF_{DOC} = DOC_{FLUX\_NATURAL} \bullet \left(1 + \Delta DOC_{DRAINAGE}\right) \bullet Frac_{DOC-CO_2}$$

Where:

EF_{DOC} = emission factor for DOC from a drained site, tonnes C $ha^{-1}yr^{-1}$

$DOC_{FLUX\_NATURAL}$ = flux of DOC from natural (undrained) organic soil, tonnes C $ha^{-1}yr^{-1}$

$\Delta DOC_{DRAINAGE}$ = proportional increase in DOC flux from drained sites relative to undrained sites

$Frac_{DOC\text{-}CO_2}$ = conversion factor for proportion of DOC converted to CO_2 following export from site

Because of the lack of data for other components of waterborne carbon fluxes and due to uncertainty about their sources and/or fate, off-site CO_2 emissions associated with waterborne carbon are only represented by DOC losses at this stage. However, if in the future adequate data become available or if adequate data are available for higher tiers, inventory compilers can expand Equation 2.4 to include POC and/or DIC (see section on methodological requirements in Appendix 2a.1).

CHOICE OF EMISSION FACTORS

Tier 1

A detailed description of the derivation of default values for Tier 1 is provided in Annex 2A.2. In summary, measurements show clear differentiation of natural DOC fluxes between boreal, temperate and tropical organic soils, and Tier 1 emission factors therefore follow a broad classification based on climate zones. Annex 2A.2 provides details and data sources for the derivation of parameter values. Note that a single default value for $\Delta DOC_{DRAINAGE}$ is currently proposed for all organic soil/land-use types, based on data from a range of studies undertaken in different climate zones. A substantial body of scientific evidence indicates a high conversion of organic soil-derived DOC to CO_2 in aquatic systems, on which basis a default $Frac_{DOC-CO_2}$ value of 0.9 (± 0.1) is proposed (see Annex 2A.2).

TABLE 2.2
DEFAULT DOC EMISSION FACTORS FOR DRAINED ORGANIC SOILS

Climate zone	$DOC_{FLUX\_NATURAL}$ ($t\ C\ ha^{-1}yr^{-1}$)	$\Delta DOC_{DRAINAGE}$[a]	$Frac_{DOC-CO_2}$	$EF_{DOC\_DRAINED}$ ($t\ C\ ha^{-1}yr^{-1}$)
Boreal	0.08 (0.06–0.11)	0.60 (0.43–0.78)	0.9 (± 0.1)	0.12 (0.07–0.19)
Temperate	0.21 (0.17–0.26)			0.31 (0.19–0.46)
Tropical	0.57 (0.49–0.64)			0.82 (0.56–1.14)

Values shown in parentheses represent 95% confidence intervals. For data sources and supporting references, see Tables 2A.2 and 2A.3.

[a] Due to the limited number of available studies, a single Tier 1 value for $\Delta DOC_{DRAINAGE}$ has been assigned to all soil types based on all available comparisons of drained and undrained sites. In the case of fens, there is more uncertainty associated with the estimation of DOC flux changes after drainage; countries may therefore choose to apply the values of $DOC_{FLUX\_NATURAL}$ given above (multiplied by $Frac_{DOC-CO_2}$ but assuming $\Delta DOC_{DRAINAGE} = 0$) or to obtain direct measurements of the DOC flux from drained sites.

Tier 2

A Tier 2 approach for estimation of DOC may follow the Tier 1 methodology provided above, but should use country-specific information where possible to refine the emission factors used. Possible refinements where supporting data are available could include:

- use of country-level measurements from natural (undrained) organic soils to obtain accurate values of $DOC_{FLUX-NATURAL}$ for that country, for example by developing specific values for raised bogs versus fens, or for blanket bogs;
- use of country-level data on the impacts of organic soil drainage on DOC flux to derive specific values of $\Delta DOC_{DRAINAGE}$ that reflect local organic soil types, and the nature of drainage practices and subsequent land use - if sufficient, robust, direct measurements are available from representative drained sites, these may be used to estimate DOC fluxes from drained sites, replacing $DOC_{FLUX\_NATURAL}$ in Equation 2.5; specific DOC flux estimates from drained organic soils in different land-use categories could also be considered where data support this level of stratification; and
- use of alternative values for $Frac_{DOC-CO2}$ where evidence is available to estimate the proportion of DOC exported from drained organic soils that is transferred to stable long-term carbon stores, such as lake or marine sediments.

Tier 3

A Tier 3 approach might include the use of more detailed data to develop and apply process models that describe DOC release as a function of vegetation composition, nutrient levels, land-use category, water table level and hydrology, as well as temporal variability in DOC release in the years following land-use change (e.g. initial drainage) and ongoing management activities (e.g. drain maintenance, forest management) (see Annex 3A.2, Chapter 3 of the *Wetlands Supplement*).

Guidance is not currently presented for the effects of land use other than drainage on DOC loss from peatlands and organic soils, such as the effects of managed burning or of intensity of agricultural use. However, these may be included in higher tier methods if sufficient evidence can be obtained to develop the associated emission factors.

CHOICE OF ACTIVITY DATA

Tier 1

Activity data consist of areas of land remaining in a land-use category on drained organic soils summarised by organic soil type, climate zones and land-use type (specifically occurrence of drainage). Total areas should be determined according to the Approaches laid out in Chapter 3, Volume 4 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. They also need to be consistent with activity data for on-site CO_2 emissions. For boreal and temperate raised bogs and fens, additional data on annual mean precipitation may be used to refine emission estimates, as shown in Table 2.2.

Tiers 2 and 3

For higher tier approaches, additional activity data requirements may include specific information on the land-use type associated with drained organic soils, and intensity of drainage. Use of a variable $Frac_{DOC\text{-}CO_2}$ value at a country level, or within a country, would require information on the characteristics of downstream river networks (e.g. water residence time, extent of lakes and reservoirs, lake sedimentation rates). A Tier 3 modelling approach could include additional information on the timing of drainage, drain maintenance and land management (e.g. forest management, influence of fertiliser application rates on DOC production).

CALCULATION STEPS FOR TIER 1

The steps for estimating off-site emissions from soil carbon on drained organic soils are as follows:

Step 1: Determine areas with drained organic soils under each land-use category for land remaining in a land-use category, disaggregated by climate domain and other appropriate factors as outlined above.

Step 2: Assign the appropriate values for $DOC_{FLUX\_NATURAL}$, $\Delta DOC_{DRAINAGE}$ and $Frac_{DOC\text{-}CO_2}$ from Table 2.2 for each land-use category and climate domain.

Step 3: Calculate EF_{DOC} for each land-use category using Equation 2.5.

Step 4: Multiply activity data by the emission factor for each land-use category and sum across land-use categories.

UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exist in estimating off-site emissions and removals: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in the emission/removal factors for Tier 1 or 2 approaches; and 3) uncertainties in the fraction of DOC that is emitted as CO_2. In general, precision of an inventory is increased and confidence ranges are smaller with more sampling to estimate values for these categories, while accuracy is more likely to be increased through implementation of higher tier methods that incorporate country-specific information.

Uncertainties for land use and management activities are the same as for on-site emissions and will not be repeated here. Uncertainty ranges (95% confidence intervals) are provided for DOC emission factors in Table 2.2. These ranges are calculated based on: 1) literature data in Annex 2A.2 based on observations from natural peatlands used to derive values of $DOC_{FLUX\text{-}NATURAL}$ in each of the peat classes used (Table 2A.2); 2) observations of $\Delta DOC_{DRAINAGE}$ from published studies (Table 2A.3); and 3) an uncertainty range for the $Frac_{DOC\text{-}CO_2}$ value of 0.8-1.0 as described above. These uncertainty ranges may be adapted or refined under Tier 2 if further sub-classification according to land-use type or intensity is undertaken, based on additional measurement data.

2.2.2 Non-CO_2 emissions and removals from drained inland organic soils

In the *2006 IPCC Guidelines*, CH_4 emissions are assumed to be negligible from all drained organic soils. Here, new methodologies and emission factors are provided for soil CH_4 emissions from drained organic soils and drainage ditches (Section 2.2.2.1).

2.2.2.1 CH_4 EMISSIONS AND REMOVALS FROM DRAINED INLAND ORGANIC SOILS

In the *2006 IPCC Guidelines*, CH_4 emissions are assumed to be negligible from all drained organic soils. However, recent evidence suggests that some CH_4 emissions can occur from the drained land surface, and also from the ditch networks constructed during drainage. Each of these emission pathways is considered here (Best & Jacobs, 1997; Minkkinen & Laine, 2006; Schrier-Uijl *et al.*, 2011; Hyvönen *et al.*, 2013).

Drainage lowers the water table, exposes formerly saturated organic soil layers to oxidation and, as described above, increases CO_2 emissions from the land surface. Drainage alters environmental factors such as temperature, reduction–oxidation potential, and the amount of easily decomposable organic matter. Drainage also affects the activity of methanogens and methanotrophs (Blodau, 2002; Treat *et al.*, 2007). Drainage increases plant root respiration and mitigates CH_4 emission dramatically (Martikainen *et al.*, 1995*a*; Strack *et al.*, 2004; Hergoualc'h &Verchot, 2012) as methanogenic bacteria thrive only in anoxic conditions. Shifts in vegetation with dominant aerenchymous species to other vegetation types will also reduce the transfer of CH_4 from the soil profile to the atmosphere (e.g. Tuittila *et al.*, 2000). In general, when organic soil is drained, natural production of CH_4 is reduced and organic soils may even become a CH_4 sink, once methanotrophs dominate the CH_4 cycle.

Ditch networks provide a further source of CH_4 emissions from drained organic soils. This occurs due to a combination of lateral CH_4 transfer from the organic soil matrix, and *in situ* CH_4 production within the ditches themselves (e.g. Roulet & Moore, 1995; van den Pol-van Dasselaar *et al.*, 1999*a*; Sundh *et al.*, 2000; Minkkinen & Laine, 2006; Teh *et al.*, 2011; Vermaat *et al.*, 2011). These emissions may approach, or even exceed, the CH_4 flux from an undrained organic soil when averaged over the land surface (Roulet & Moore, 1995; Schrier-Uijl *et al.*, 2011). Emission/removal factors for ditch CH_4 emissions were compiled from available published literature (see Annex 2A.1). We present only general factors for ditches because of limited data. Effects of ditch maintenance, deepening and other factors may be addressed at higher tiers.

CHOICE OF METHOD

Tier 1

CH_4 emissions from the land surface are estimated using a simple emission factor approach (see Equation 2.6), depending on climate and type of land use. The default methodology considers boreal, temperate and tropical climate zones, and nutrient-rich/nutrient-poor organic soils. Different land uses imply drainage to different depths. The CH_4 emission factors depend on gas flux measurements, either from closed chambers or (for land-surface emissions) from eddy covariance.

Ditch CH_4 emissions should be quantified for any area of drained organic soil where there are ditches or drainage canals (note that CH_4 may also be emitted from ditches within rewetted organic soils where ditches remain present, although at Tier 1 it is assumed that this flux equates to that from the remainder of the rewetted site; see Chapter 3 of the *Wetlands Supplement*). Estimation of ditch CH_4 emissions requires information on the land-use class and on the area of the landscape occupied by the drainage ditch network, $Frac_{ditch}$.

EQUATION 2.6

ANNUAL CH_4 EMISSIONS FROM DRAINED ORGANIC SOILS

$$CH_{4\_organic} = \sum_{c,n,p} \left(A_{c,n,p} \bullet \left((1 - Frac_{ditch}) \bullet EF_{CH_4\_land_{c,n}} + Frac_{ditch} \bullet EF_{CH_4\_ditch_{c,p}} \right) \right)$$

Where:

$CH_{4\_organic}$ = annual CH_4 loss from drained organic soils, kg CH_4 yr^{-1}

$A_{c,n,p}$ = land area of drained organic soils in a land-use category in climate zone c, nutrient status n and soil type p, ha

$EF_{CH4\_landc,n}$ = emission factors for direct CH_4 emissions from drained organic soils, by climate zone c and nutrient status n, kg CH_4 $ha^{-1}yr^{-1}$

$EF_{CH4\_ditchc,p}$ = emission factors for CH_4 emissions from drainage ditches, by climate zone c and soil type p, kg CH_4 $ha^{-1}yr^{-1}$

$Frac_{ditch}$ = fraction of the total area of drained organic soil which is occupied by ditches (where "ditches" are considered to be any area of manmade channel cut into the peatland). The ditch area may be calculated as the width of ditches multiplied by their total length. Where ditches are cut vertically, ditch width can be calculated as the average distance from bank to bank. Where ditch banks are sloping, ditch width should be calculated as the average width of open water plus any saturated fringing vegetation.

Tier 2

The Tier 2 approach for estimating CH_4 emissions from drained organic soils incorporates country-specific information into Equation 2.6. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Under Tier 2, the emission factors for CH_4 from the surface of drained organic soils can be further differentiated by drainage depth, land-use subcategories or vegetation type (such as presence or absence of plant species that act as transporters of CH_4 from the soil to the atmosphere). Guidance for further stratification follows the principles given in Section 2.2.1.1 of this Chapter.

Tier 2 approaches for CH_4 emissions from drainage ditches generally follow the Tier 1 approach described above, with country-specific measurements or estimates of annual mean ditch CH_4 emissions, and national or regional estimates of fractional ditch area that reflect local drainage practices. The land-use sub-categories in Table 2.4 may be expanded or subdivided where appropriate to reflect the range of observed land use on drained organic soils.

Tier 3

Tier 3 methods for estimating CH_4 emissions from drained organic soils involve a comprehensive understanding and representation of the dynamics of CH_4 emissions and removals on managed peatlands and organic soils, including the effect of site characteristics, peat/soil type, peat degradation and depth, land-use intensity, drainage depth, management systems, and the level and kinds of fresh organic matter inputs. Emission spikes may also occur, for example during spring thaw or strong rains or when debris from ditch dredging is deposited on adjacent land.

For CH_4 emissions from drainage ditches, development of a Tier 3 approach could take account of the influence of land-management activities (e.g. organic matter additions to agricultural land) on substrate supply for methane production in ditches, of possible short-term pulses of ditch CH_4 emissions associated with land-use change, and of the legacy effects of past land use (e.g. nutrient-enriched soils). Information on drainage ditch characteristics and maintenance may be used to refine ditch CH_4 emission estimates, for example taking account of: 1) the potential effects of plant or algal growth within ditches; 2) presence of subsurface drainage in Cropland and Grassland; 3) water flow rates, transport length of water and oxygen status; 4) ditch maintenance activities; and 5) the deposition of organic material removed from ditches onto adjacent land areas.

CHOICE OF EMISSION FACTORS

Tier 1

Default emission factors for the Tier 1 method are provided in Table 2.3 for EF_{CH4_land} and Table 2.4 for EF_{CH4_ditch}. EF_{CH4_land} were derived from the mean of all data within each land-use class, typically from chamber measurements, and uncertainty ranges were calculated as 95% confidence intervals. References are given in Table 2.3.

At present, data from literature are sufficient to provide Tier 1 default values of EF_{CH4_ditch} for each of the four major land-use classes on drained organic soils (Forest Land, Grassland, Cropland and Wetlands used for peat extraction) in boreal and temperate regions (Table 2.4). In the case of Cropland, because no data are currently available, Tier 1 default values for deep-drained Grassland may be applied. Limited data on ditch CH_4 emissions are currently available for tropical organic soils, and a single Tier 1 emission factor is therefore provided for all drained land-use classes. Scientific background for EF_{CH4_ditch} and $Frac_{ditch}$ is given in Annex 2A.2.

Tier 2

Tier 2 emission factors EF_{CH4_land} may be based on country- or region-specific emission factors for CH_4 emissions from the surface of drained organic soils. These allow further stratification of land-use categories by drainage class, nutrient status or vegetation characteristics.

Methane emissions from drainage ditches will vary according to peat/soil type, land-use type, drainage intensity and (for agriculturally managed areas) land-use intensity. For example, labile organic matter and nutrient inputs from terrestrial areas are likely to increase CH_4 production in ditches (Schrier-Uijl *et al*., 2011). The Tier 1 emission factors EF_{CH4_ditch} provided are based on measurements from ditches located within the organic layer. Subsurface drainage systems may represent additional sources of CH_4 emissions in Cropland and Grassland, and could be incorporated into the approach provided that appropriate measurement data are available. Countries are encouraged to obtain new measurement data for significant land-use classes to enhance the current dataset, and to develop country-specific Tier 2 emission factors. Sharing of data between countries may be appropriate where environmental conditions and practices are similar.

Tier 3

A Tier 3 approach for CH_4 emissions from drained organic soils might include further details and processes or capture seasonal dynamics of CH_4 emissions as additional elements of stratification or by dynamic modelling.

A Tier 3 approach for CH_4 emissions from drainage ditches might include the use of more detailed data to develop and apply process models that describe CH_4 emissions as a function of drainage ditch characteristics and maintenance, for example taking account of: 1) the potential effects of plant or algal growth within ditches; 2) water flow rates, transport length of water and oxygen status; 3) ditch maintenance activities; and 4) the deposition of organic material removed from ditches onto adjacent land areas.

A Tier 3 approach to estimating ditch CH_4 emissions could take account of the temporal variability of hydrological conditions, labile substrate and nutrient supply, and controls on the composition of in-ditch-vegetation that might enhance or reduce emission rates.

Emissions from stockpiles of drying peat are uncertain and stockpiles may release or consume CH_4 at different rates than the excavation field, but data are not at present sufficient to provide guidance. Methods for estimating this flux may be developed for Tier 3 approaches.

TABLE 2.3
TIER 1 CH_4 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS ($EF_{CH_4\_LAND}$) IN ALL LAND-USE CATEGORIES [a]

Land-use category		**Climate / vegetation zones**	**Emission factor[a] (kg CH_4 $ha^{-1}yr^{-1}$)**	**95% confidence interval[b] (centred on mean)**		**No. of sites**	**Citations/comments**
Forest Land, drained	Nutrient-poor	Boreal	7.0	2.9	11	47	Komulainen *et al*., 1998; Lohila *et al*., 2011; Maljanen *et al*., 2006; Martikainen *et al*., 1992, 1993, 1995*b*; Minkkinen & Laine, 2006; Minkkinen *et al*., 2007*a*; Nykänen *et al*., 1998; Ojanen *et al*., 2010, 2013
	Nutrient-rich	Boreal	2.0	-1.6	5.5	83	Komulainen *et al*., 1998; Laine *et al*., 1996; Maljanen *et al*., 2001*b*, 2003*b*, 2006; Mäkiranta *et al*., 2007; Martikainen *et al*., 1992, 1995*b*; Minkkinen & Laine, 2006; Minkkinen *et al*., 2007*a*; Nykänen *et al*., 1998; Ojanen *et al*., 2010, 2013
Forest Land, drained		Temperate	2.5	-0.60	5.7	13	Glenn *et al*., 1993; Moore & Knowles, 1990; Sikström *et al*., 2009; von Arnold *et al*., 2005*a*, *b*; Weslien *et al*., 2009; Yamulki *et al*., 2013
Forest Land and cleared Forest Land (shrubland[c]), drained		Tropical/ Subtropical	4.9	2.3	7.5	7	Furukawa *et al*., 2005; Hirano *et al*., 2009; Jauhiainen *et al*., 2008
Forest plantations, drained[d]		Tropical/ Subtropical	2.7	-0.9	6.3	5	Basuki *et al*., 2012; Jauhiainen *et al*., 2012*c*
Plantation: oil palm		Tropical/ Subtropical	0	0	0	1	Melling *et al*., 2005*b*
Plantation: sago palm		Tropical/ Subtropical	26.2	7.2	45.3	6	Inubushi *et al*., 1998; Melling *et al*., 2005*b*; Watanabe *et al*., 2009
Cropland, drained		Boreal and Temperate	0	-2.8	2.8	38	Augustin, 2003; Augustin *et al*., 1998; Drösler *et al*., 2013; Elsgaard *et al*., 2012; Flessa *et al*., 1998; Kasimir-Klemedtsson *et al*., 2009; Maljanen *et al*., 2003*a*, *b*, 2004, 2007; Petersen *et al*., 2012; Regina *et al*., 2007; Taft *et al*., 2013
Cropland		Tropical/ Subtropical	7.0	0.3	13.7	5	Furukawa *et al*., 2005; Hirano *et al*., 2009

TABLE 2.3 (CONTINUED)
TIER 1 CH_4 EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS ($EF_{CH_4\_LAND}$) IN ALL LAND-USE CATEGORIES [a]

Land-use category	Climate / vegetation zones	Emission factor[a] (kg CH_4 $ha^{-1}yr^{-1}$)	95% confidence interval[b] (centred on mean)		No. of sites	Citations/comments
Rice[e]	Tropical/ Subtropical	143.5	63.2	223.7	6	Furukawa *et al*., 2005; Hadi *et al*., 2005; Inubushi *et al*., 2003
Grassland, drained	Boreal	1.4	-1.6	4.5	12	Grønlund *et al*., 2006; Guðmundsson & Óskarsson, 2008; Hyvönen *et al*., 2009; Maljanen *et al*., 2001*b*, 2003*b*, 2004, 2010*b, c*; Nykänen *et al*., 1995; Regina *et al*., 2007
Grassland, drained, nutrient-poor	Temperate	1.8	0.72	2.9	9	Drösler *et al*., 2013; Kasimir-Klemedtsson *et al*., 2009; van den Bos, 2003
Grassland, deep-drained, nutrient-rich	Temperate	16	2.4	29	44	Augustin *et al*., 1996; Best & Jacobs, 1997; Drösler *et al*., 2013; Flessa & Beese, 1997; Flessa *et al*., 1998; Jacobs *et al*., 2003; Kroon *et al*., 2010; Langeveld *et al*., 1997; Meyer *et al*., 2001; Nykänen *et al*., 1995; Petersen *et al*., 2012; Schrier-Uijl *et al*., 2010*a*, *b*; Teh *et al*., 2011; van den Bos, 2003; van den Pol-van Dasselaar *et al*., 1997; Wild *et al*., 2001
Grassland, shallow-drained, nutrient-rich	Temperate	39	-2.9	81	16	Augustin, 2003; Drösler *et al*., 2013; Jacobs *et al*., 2003; van den Pol-van Dasselaar *et al*., 1997
Grassland	Tropical/ Subtropical	7.0	0.3	13.7	5	Same emission factor as tropical Cropland
Peat Extraction	Boreal and Temperate	6.1	1.6	11	15	Hyvönen *et al*., 2009; Nykänen *et al*., 1996; Strack & Zuback, 2013; Sundh *et al*., 2000; Tuittila *et al*., 2000; Waddington & Day, 2007
Settlements	All climate zones	There is no fixed default emission/removal factor for Settlements. For this category, it is *good practice* to take the default emission/removal factor from Table 2.3 of the land-use category that is closest to national conditions of drained organic soils under Settlements. Information about national conditions could include drainage level, vegetation cover or other management activities. For example, drained organic soils in urban green areas, parks or gardens could use the default Tier 1 emission/removal factor for Grassland, deep-drained given in Table 2.3.				
Other Land	All climate zones	*Other Land Remaining Other Land*: 0 *Land Converted to Other Land*: maintain emission factor for previous land-use category				

[a] Mean

[b] Some confidence intervals contain negative values. This indicates that, while the mean emission factor is zero or a net CH_4 emission, a net CH_4 uptake has been observed in some studies.

[c] Shrubland refers to any type of land sparsely or fully covered with shrubs or trees that may fulfil the national forest definition. It extends to degraded lands that cannot be clearly classified as forest or non-forest.

[d] Number derived solely from acacia plantation data.

[e] The default value applies to countries without data on the flooding regime for rice on organic soils. Countries with data on the flooding regime for rice on organic soils may continue to use the methodologies and emission factors provided in the *2006 IPCC Guidelines*.

Plantations can be defined as Forest Land or Cropland or any other land-use category, according to national definitions. It is *good practice* to report plantations in the appropriate national land-use category according to national land-use definitions.

CHOICE OF ACTIVITY DATA

Tier 1

It is *good practice* to use the same activity data for estimating CO_2, N_2O and CH_4 emissions from drained organic soils. Information on obtaining these data is provided in Section 2.2.1 above. For countries in boreal and temperate regions using the Tier 1 method, if available information does not allow stratification by nutrient status of organic soils, countries may rely on guidance given in Section 2.2.1.1.

Activity data required to estimate CH_4 emissions from drainage ditches at Tier 1 consist of areas of drained organic soils disaggregated by land-use category (Forest Land, Grassland, Cropland and Wetlands used for peat extraction) as shown in Table 2.4. Fractional ditch areas recorded in published studies are given for individual sites in Table 2A.1 and these data have been used to provide indicative $Frac_{ditch}$ values by land-use class in Table 2.4. However, it should be noted that these proportions are likely to vary between countries and it is therefore *good practice* to derive country-specific activity data on fractional ditch areas wherever possible, to reflect local land-use practices. This fractional ditch area may depend on the topographic situation and on organic soil properties rather than on land use alone. Fractional ditch area can be calculated from spatially explicit information about ditch and canal networks. From these the length and width of ditches can be derived, or alternatively ditch spacing and ditch width on organic soils, giving the ditch area on organic soils. This geometrical information is converted to fractional ditch area by dividing the ditch area on organic soils by the area of drained organic soils.

Tiers 2 and 3

Activity data required for higher tier methods are likely to include more detailed information on land use, in particular land-use intensity within Grassland and Cropland classes. Further stratification may be necessary for other classes if sufficient data become available to estimate emission factors, e.g. for cleared peat swamp forest, oil palm, or pulpwood plantation in tropical peat areas.

Activity data for higher tier methods may be spatially explicit and consist of areas of drained organic soils managed for different forest types, peat extraction, production systems, horticulture and plantations, disaggregated according to the nutrient status of the organic soil if relevant. More sophisticated estimation methodologies will require the determination of areas in different phases of land uses with longer-term rhythms such as age-classes in Forest Land or in a peat extraction operation, where on abandoned areas drainage or the effects of former peat extraction are still present. Land-use intensity, particularly fertiliser and organic matter addition, may be used to refine CH_4 emission estimates for Grassland and Cropland, as emissions are likely to change under more intensive management systems.

To estimate CH_4 emissions from drainage ditches, additional activity data are required on fractional ditch area within each land-use category. Country-specific values of fractional ditch areas are used to reflect drainage methodologies such as typical ditch spacing, depth, width and length, maintenance (such as vegetation clearance) and land-use practices. Fractional ditch area can be stratified by type of organic soil or topographic situation, peat/soil properties, and land use.

Activity data for CH_4 emissions from drainage ditches could incorporate additional information on water table level and variability (such as seasonal water management regime), flow rates, in-ditch vegetation and land-use factors affecting substrate supply for methanogenesis, such as livestock density and fertiliser application in intensive Grassland and Cropland. Incorporating seasonal and short-term controls on emissions would require additional activity data on the nature and timing of agricultural activities (such as organic matter additions) and on hydrological parameters.

CALCULATION STEPS FOR TIER 1

The steps for estimating CH_4 emissions from drained organic soils are as follows:

Step 1: Determine areas with drained organic soils under each land-use category for lands remaining in a land-use category, disaggregated by climate domain and other appropriate factors as outlined above and consistent with estimates of on-site CO_2 emissions from drained organic soils. Where needed for Tier 1 emission factors, land areas are further stratified into nutrient-rich and nutrient-poor organic soils. Temperate nutrient-rich Grassland is further stratified into shallow-drained and deep-drained classes.

Step 2: Assign the appropriate value for the fraction of areas covered by ditches using national statistics. If statistics are not available, values given in Table 2.4 provide appropriate defaults.

Step 3: Assign the appropriate emission factor values (EF_{CH4_land} and EF_{CH4_ditch}) from Tables 2.3 and 2.4, respectively.

Step 4: Multiply each area by the appropriate emission factor using Equation 2.6 and sum across land-use categories.

TABLE 2.4
DEFAULT CH_4 EMISSION FACTORS FOR DRAINAGE DITCHES

Climate zone	Land use	EF_{CH4_ditch} (kg CH_4 ha^{-1} yr^{-1})	Uncertainty range^a (kg CH_4 $ha^{-1}yr^{-1}$)	No. of sites	$Frac_{ditch}$ (indicative values^e)	Citations
Boreal / Temperate	Drained Forest Land Drained Wetlands^b	217	41–393	11	0.025	Cooper & Evans, 2013; Glagolev *et al*., 2008; Minkkinen & Laine, 2006 (two study areas); Roulet & Moore, 1995 (three study areas); Sirin *et al*., 2012 (three study areas); von Arnold *et al*., 2005*b*
	Shallow-drained Grassland	527	285–769	5	0.05	Best & Jacobs, 1997; Hendriks *et al*., 2007, 2010; McNamara, 2013; van den Pol-van Dasselaar *et al*., 1999*a*; Vermaat *et al*., 2011
	Deep-drained Grassland Cropland^c	1165	335–1995	6	0.05	Best & Jacobs, 1997; Chistotin *et al*., 2006; Schrier-Uijl *et al*., 2010*b*, 2011; Sirin *et al*., 2012; Teh *et al*., 2011; Vermaat *et al*., 2011
	Peat Extraction	542	102–981	6	0.05	Chistotin *et al*., 2006; Hyvönen *et al*., 2013; Nykänen *et al*., 1996; Sirin *et al*., 2012; Sundh *et al*., 2000; Waddington & Day, 2007
Tropical	All land uses involving drainage	2259	599–3919^d	2	0.02	Jauhiainen & Silvennoinen, 2012 (drained and abandoned, and pulpwood plantations)

[a] Values represent 95% confidence intervals unless otherwise stated

[b] Ditch CH_4 emissions from Wetlands subject to drainage but no other land-use modifications are assumed to be equivalent to those from organic soils drained for forestry.

[c] Ditch CH_4 emissions from Cropland are assumed to be the same as those from high-intensity Grassland, for which more data exist.

[d] Due to limited data for CH_4 emissions from tropical drainage channels, the range of measurements is shown, rather than the 95% confidence intervals.

[e] Indicative values for $Frac_{ditch}$ within each class are derived from the mean of studies reporting CH_4 emission values for this class. Note that studies from The Netherlands were not included in this calculation, because they are characterised by much higher fractional ditch areas (0.1–0.25) that are not typical of drained organic soils in other countries.

UNCERTAINTY ASSESSMENT

The principal sources of uncertainty for CH_4 emissions from drained organic soils are activity data, including associated information on the fraction of drained areas covered by ditches, and emission factors. Uncertainty ranges are provided in Table 2.3 for values of EF_{CH4_land} and Table 2.4 for values of EF_{CH4_ditch} for each organic soil/land-use category. Uncertainty ranges in Table 2.3 are expressed as 95% confidence intervals or as standard errors, depending on the number of studies available. The major source of uncertainty in these values is simply the small number of studies on which many Tier 1 estimates are based, and the high degree of heterogeneity in measured fluxes between different studies undertaken within some classes. Confidence intervals (95%) have been calculated for all classes other than the drained tropical organic soil class, for which only one study (Jauhiainen & Silvennoinen, 2012) is available, which provides estimates of ditch CH_4 emissions from areas of drained, deforested and abandoned organic soils, and pulpwood plantations. For the drained tropical organic soils category, the uncertainty range is provided by the lower (abandoned) and higher (pulpwood plantations) emission values recorded.

The final calculation of $CH_{4\_organic}$ is also sensitive to uncertainties in activity data, and in particular to data used to estimate the proportion of the land area that is occupied by drainage ditches, $Frac_{ditch}$. Many countries lack such data and although activity data should be country-specific, even for Tier 1, indicative values from Table 2A.1 can be used at the discretion of the inventory compiler. Uncertainty assessments should therefore also take account of this source of uncertainty in calculating total CH_4 emissions from drained organic soils.

2.2.2.2 N_2O EMISSIONS FROM DRAINED INLAND ORGANIC SOILS

N_2O emissions from soils are produced by the microbiological processes of nitrification and denitrification (to N_2O or N_2) (Firestone & Davidson, 1989; Davidson, 1991). These processes are controlled by several factors, including water-filled pore space (Davidson, 1991; Aulakh & Bijay-Singh, 1997; Dobbie *et al.*, 1999; Ruser *et al.*, 2001), temperature (Keeney *et al.*, 1979; Kroon *et al.*, 2010), and concentration of mineral nitrogen (Ryden & Lund, 1980; Firestone & Davidson, 1989; Bremner, 1997).

Drained organic soils emit significant amounts of N_2O, whereas emissions from wet organic soils are close to zero (Kasimir-Klemedtsson *et al.*, 1997; Flessa *et al.*, 1998; Couwenberg *et al.*, 2011). A main reason for increased N_2O emissions is nitrogen mineralisation associated with organic matter decomposition in drained organic soils (Höper, 2002). Emissions from this N mineralisation will be dealt with here. Other sources of anthropogenic N in organic soils include nitrogen fertiliser, application of crop residues and organic amendments. These emissions from other N sources are dealt with in Chapter 11, Volume 4 of the *2006 IPCC Guidelines* and in all earlier guidance.

Most of the published data on N_2O fluxes from drained organic soils refer to boreal and temperate ecosystems and these data served as the basis for the emission factors given in the *2006 IPCC Guidelines*. With new studies published since 2005, there are enough data to derive separate N_2O emission factors for Forest Land, Cropland, Grassland and Peatlands under Peat Extraction in boreal and temperate zones. These new values replace the values given in Table 7.6, Chapter 7, Volume 4 of the *2006 IPCC Guidelines*.

There are still only limited data available for drained tropical organic soils. However, the studies that have been published over the past decade provide enough data to develop Tier 1 emission factors for the first time.

CHOICE OF METHOD

Tier 1

This section presents the equation for estimating direct emissions of N_2O due to drainage of organic soils. The revisions presented here, as shown in Equation 2.7, are applicable to Equation 11.1 presented in Chapter 11, Volume 4 of the *2006 IPCC Guidelines*. This Equation is used to estimate N_2O for specific land-use categories, but there are not enough data available to develop coefficients to modify emission factors by condition-specific variables (e.g. variations in drainage depths). Equations 11.1 and 11.2 have been modified to include variables for the boreal climate zone as well by adding terms $F_{OS,\ CG\ Bor\ NR}$, $F_{OS,\ CG,\ Bor\ NP}$, $F_{OS,\ F,\ Bor,\ NR}$ and $F_{OS,\ F\ Bor\ NP}$ (the subscripts CG, F, Bor, NR and NP refer to Cropland and Grassland, Forest Land, Boreal, Nutrient-Rich and Nutrient-Poor, respectively) and their respective emission factors.

Direct N_2O emissions from managed soils are estimated using Equation 11.1 in Chapter 11, Volume 4 of the *2006 IPCC Guidelines*. This Equation has three segments: one for emissions associated with N inputs, one for organic soils and one for urine and dung inputs during grazing. In this section, updates are provided for the second segment focusing on organic soils as follows:

EQUATION 2.7
DIRECT N_2O EMISSIONS FROM MANAGED/DRAINED ORGANIC SOILS

$$N_2O-N_{OS}=\begin{bmatrix}\left(F_{OS,CG,Bor}\bullet EF_{2CG,Bor}\right)+\left(F_{OS,CG,Temp}\bullet EF_{2CG,Temp}\right)+\left(F_{OS,CG,Trop}\bullet EF_{2CG,Trop}\right)+\\ \left(F_{OS,F,Bor,NR}\bullet EF_{2F,Bor,NR}\right)+\left(F_{OS,F,Temp,NR}\bullet EF_{2F,Temp,NR}\right)+\\ \left(F_{OS,F,Bor,NP}\bullet EF_{2F,Bor,NP}\right)+\left(F_{OS,F,Temp,NP}\bullet EF_{2F,Temp,NP}\right)+\left(F_{OS,F,Trop}\bullet EF_{2F,Trop}\right)\end{bmatrix}$$

Where:

$N_2O–N_{OS}$ = Annual direct N_2O–N emissions from managed/drained organic soils, kg N_2O–N yr^{-1}

F_{OS} = Annual area of managed/drained organic soils, ha (note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient-Rich and Nutrient-Poor, respectively)

EF_2 = Emission factor for N_2O emissions from drained/managed organic soils, kg N_2O–N $ha^{-1}yr^{-1}$; (equivalent to Table 11.1, Chapter 11, Volume 4 of the *2006 IPCC Guidelines* but using updated emission factor values provided in Table 2.5 below; note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient-Rich and Nutrient-Poor, respectively.).

Tier 2

Tier 2 estimates are to be based on the Tier 1 Equation 2.7, but use country- or region-specific emission factors. These can be further stratified by drainage class, nutrient status of organic soils or other criteria used for stratifying organic soils for direct N_2O emissions. The corresponding emission factors are country- or region-specific and take into account the land-management systems. Tier 2 emission factors can follow the Tier 1 assumption that N mineralisation from degrading organic matter exceeds the amount of N input so that measured N_2O emissions are attributed in their entirety to the drained organic soil.

Tier 3

Tier 3 approaches can attribute N_2O emissions from drained organic soils separately to the mineralisation of peat or organic matter versus N input by fertiliser, crop residues and organic amendments. Attribution could rely on the fraction of N_2O released by N_2O emissions peaks after N fertilisation, or by subtracting a fertiliser emission factor from total N_2O emissions. Nitrogen mineralisation from the drained organic soil can be estimated by CO_2-C emissions from the drained organic soil and the C/N ratio of the topsoil; this value could be used to predict N_2O emissions.

Tier 3 methods are based on modelling or measurement approaches. Models can simulate the relationship between the soil and environmental variables that control the variation in N_2O emissions and the size of those emissions (Stehfest & Bouwman, 2006; Kroon *et al.*, 2010; Dechow & Freibauer, 2011). These models can be used at larger scales where measurements are impractical. Models should only be used after validation against representative measurements that capture the variability of land use, management practices and climate present in the inventory (IPCC, 2010).

CHOICE OF EMISSION FACTORS

Tier 1

Emission factors for drained organic soils

The *2006 IPCC Guidelines* provide emission factors that were partly disaggregated for land-use types or climatic zones (Table 11.1, Chapter 11, Volume 4). The increased availability of scientific data allows for an improved choice of default emission factors (Table 2.5). Nutrient-poor and nutrient-rich organic soils drained for forestry have different N_2O emissions. Cropland and Grassland are established on nutrient-rich organic soil or are amended for better nutrient availability and are here considered to be nutrient-rich. Peat extraction occurs both on nutrient-poor (bogs) and on nutrient-rich (fens) peatlands. It is common for the residual bottom peat layers of peat extraction sites to consist of minerogenous but recalcitrant nutrient-rich peat. There are not enough data available to disaggregate peat extraction areas by peat types.

Default emission factors were derived from the mean of all data within each land-use class, typically from chamber measurements. Uncertainty ranges were calculated as 95% confidence intervals. References are given in Table 2.5.

TABLE 2.5
TIER 1 DIRECT N_2O EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES[a]

Land-use category		**Climate / vegetation zone**	**Emission factor (kg N_2O-N $ha^{-1}yr^{-1}$)**	**95% confidence interval**		**No. of sites**	**Citations/comments**
Forest Land, drained	Nutrient-poor	Boreal	0.22	0.15	0.28	43	Lohila *et al*., 2011; Maljanen *et al*., 2006; Martikainen *et al*., 1993, 1995*a*; Ojanen *et al*., 2010, 2013; Regina *et al*., 1996
	Nutrient-rich	Boreal	3.2	1.9	4.5	75	Ernfors *et al*., 2011; Mäkiranta *et al*., 2007; Maljanen *et al*., 2001*b*, 2003*a*, 2006, 2010*a*; Martikainen *et al*., 1993, 1995*a*; Ojanen *et al*., 2010, 2013; Pihlatie *et al*., 2004; Regina *et al*., 1998; Saari *et al*., 2009
Forest Land, drained		Temperate	2.8	-0.57	6.1	13	Sikström *et al*., 2009; von Arnold *et al*., 2005*a*, *b*; Weslien *et al*., 2009; Yamulki *et al*., 2013
Forest Land and cleared Forest Land (shrubland[b]), drained		Tropical/ Subtropical	2.4	1.3	3.5	10	Furukawa *et al*., 2005; Jauhiainen *et al*., 2012*b*; Takakai *et al*., 2006
Plantation: oil palm		Tropical/ Subtropical	1.2	n.a.	n.a.	1	Melling *et al*., 2007*b*
Plantation: sago palm		Tropical/ Subtropical	3.3	n.a.	n.a.	1	Melling *et al*., 2007*b*
Cropland, drained		Boreal and Temperate	13	8.2	18	36	Augustin *et al*., 1998; Drösler *et al*., 2013; Elsgaard *et al*., 2012; Flessa *et al*., 1998; Kasimir-Klemedtsson *et al*., 2009; Maljanen *et al*., 2003*a*, *b*, 2004, 2007; Petersen *et al*., 2012; Regina *et al*., 2004; Taft *et al*., 2013
Cropland except rice		Tropical/ Subtropical	5.0	2.3	7.7	8	Furukawa *et al*., 2005; Jauhiainen *et al*., 2012*b*; Takakai *et al*., 2006
Rice		Tropical/ Subtropical	0.4	-0.1	0.8	6	Furukawa *et al*., 2005; Hadi *et al*., 2005; Inubushi *et al*., 2003
Grassland, drained		Boreal	9.5	4.6	14	16	Grønlund *et al*., 2006; Hyvönen *et al*., 2009; Jaakkola, 1985; Maljanen *et al*., 2001*b*, 2003*a*, 2004, 2009, 2010*b*; Nykänen *et al*., 1995; Regina *et al*., 1996, 2004
Grassland, drained, nutrient-poor		Temperate	4.3	1.9	6.8	7	Drösler *et al*., 2013; Kasimir-Klemedtsson *et al*., 2009

TABLE 2.5 (CONTINUED)
TIER 1 DIRECT N_2O EMISSION/REMOVAL FACTORS FOR DRAINED ORGANIC SOILS IN ALL LAND-USE CATEGORIES[a]

Land-use category	**Climate / vegetation zone**	**Emission factor ($kg\ N_2O\text{-}N\ ha^{-1}yr^{-1}$)**	**95% confidence interval**		**No. of Sites**	**Citations/comments**
Grassland, deep-drained, nutrient-rich	Temperate	8.2	4.9	11	47	Augustin & Merbach, 1998; Augustin *et al*., 1996, 1998; Drösler *et al*., 2013; Flessa & Beese, 1997; Flessa *et al*., 1998; Jacobs *et al*., 2003; Kroon *et al*., 2010; Langeveld *et al*., 1997; Meyer *et al*., 2001; Nykänen *et al*., 1995; Petersen *et al*., 2012; Teh *et al*., 2011; van Beek *et al*., 2010; Velthof *et al*., 1996; Wild *et al*., 2001
Grassland, shallow-drained, nutrient-rich	Temperate	1.6	0.56	2.7	13	Drösler *et al*., 2013; Jacobs *et al*., 2003
Grassland	Tropical/ Subtropical	5.0	2.3	7.7	8	The emission factor for tropical Cropland can be used
Peatland Managed for Extraction	Boreal and Temperate	0.30	-0.03	0.64	4	Hyvönen *et al*., 2009; Nykänen *et al*., 1996; Regina *et al*., 1996
Peatlands Managed for Extraction	Tropical/ Subtropical	3.6	0.2–5.0			Emission factors from Table 7.6 of Chapter 7, Volume 4 of the *2006 IPCC Guidelines* can be used.
Settlements	All climate zones	There is no fixed default emission/removal factor for Settlements. For this category, it is *good practice* to take the default emission/removal factor from Table 2.5 of the land-use category that is closest to national conditions of drained organic soils under Settlements. Information about national conditions could include drainage level, vegetation cover or other management activities. For example, drained organic soils in urban green areas, parks or gardens could use the default Tier 1 emission/removal factor for Grassland, deep-drained given in Table 2.5.				
Other Lands	All climate zones	*Other Land Remaining Other Land*: 0 *Land Converted to Other Land*: maintain emission factor of previous land-use category				

[a] Mean

[b] Shrubland refers to any type of land sparsely or fully covered with shrubs or trees that may fulfil the national forest definition. It extends to degraded lands that cannot be clearly classified as forest or non-forest.

Plantations can be defined as Forest Land or Cropland. The attribution to Cropland made in this table is not binding. It is *good practice* to report plantations in the appropriate national land-use category according to national land-use definitions.

In the *2006 IPCC Guidelines*, emission factors were provided for $EF_{2CG,\ Trop}$ and $EF_{2F,\ Trop}$, based on the expectation that net mineralisation was twice as high in tropical soils as in temperate soils. Research in tropical soils suggests that net mineralisation is not a useful predictor of N_2O flux and that net nitrification or the nitrate portion of the inorganic-N pool are better predictors (Verchot *et al*., 1999, 2006; Ishizuka *et al*., 2005). It also needs to be highlighted that all measurements of N_2O emissions on tropical organic soils to date are from Southeast Asia and from a very limited number of studies. Nonetheless these emission factors are to be used for all tropical ecosystems until better data become available.

Tier 2

Tier 2 emission factors may be based on country- or region-specific emission factors for N_2O emissions from the surface of drained organic soils. These allow further stratification of land-use categories by drainage class, nutrient status or vegetation characteristics. Countries are encouraged to obtain new measurement data for significant land-use classes to enhance the current dataset, and to develop country-specific Tier 2 emission factors. Sharing of data between countries may be appropriate where environmental conditions and practices are similar.

Tier 3

Tier 3 emission factors or relations are based on country-specific emission data and models calibrated for management practices such as: 1) drainage intensity; 2) crop, livestock or forest type; 3) fertiliser or organic matter additions; 4) peat extraction technology; and 5) the phases of peat extraction or other relevant factors for N_2O emissions.

CHOICE OF ACTIVITY DATA

Activity data consist of areas of land remaining in a land-use category on drained organic soils stratified by major land-use types, management practices and disturbance regimes. Total areas should be determined according to the Approaches laid out in Chapter 3, Volume 4 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. Stratification of land-use categories according to climate regions, based on default or country-specific classifications, can be accomplished with overlays of land use on suitable climate and soil maps.

Tier 1

It is *good practice* to use activity data for N_2O emissions consistent with activity data for CO_2 and CH_4 emissions from soils. Guidance for activity data is given in the respective sections in this Chapter.

Tiers 2 and 3

Activity data required for higher tier methods are likely to include more detailed information on land use, in particular land-use intensity within Grassland and Cropland classes. Further stratification may be necessary for other classes if sufficient data become available to estimate emission factors, e.g. for cleared peat swamp forest, oil palm or pulpwood plantations in tropical peat areas.

Activity data for higher tier methods may be spatially explicit and consist of areas of drained organic soils under different forest types, peat extraction, cultivation systems, horticulture and plantations, disaggregated according to nutrient status of the organic soil if relevant, and annual peat production data. More sophisticated estimation methodologies will require the determination of areas in different phases of land uses with longer-term rhythms such as age-classes in Forest Land or in a peat extraction cycle, where on abandoned areas drainage or the effects of former peat extraction are still present.

CALCULATION STEPS FOR TIER 1

The steps for estimating N_2O emissions on drained organic soils are as follows:

Step 1: Determine areas with drained organic soils under each land-use category for lands remaining in a land-use category, disaggregated by climate domain and other appropriate factors as outlined above. Where needed for Tier 1 emission factors, land areas are further stratified into nutrient-rich and nutrient-poor organic soils. Temperate nutrient-rich Grassland is further stratified into shallow-drained and deep-drained classes.

Step 2: Assign the appropriate values for EF_2 from Table 2.5 for each land-use category, climate domain, nutrient status, and drainage class stratum.

Step 3: Multiply activity data by the emission factor for each land-use category according to Equation 2.7.

UNCERTAINTY ASSESSMENT

Uncertainties in estimates of direct N_2O emissions from drained organic soils are caused by uncertainties related to emission factors (see Table 2.5 for uncertainty ranges), inter-annual variability associated with temperature and precipitation, activity data, lack of coverage of measurements, spatial aggregation and lack of information on specific on-farm practices.

Additional uncertainty will be introduced in an inventory when emission factors are derived from measurements that are not representative of the variation of conditions in a country. Because of very high spatial variability of N_2O emissions from soils, most estimates have large standard errors relative to the mean flux. In general, the uncertainty of activity data will be lower than that of the emission factors. Additionally, uncertainties may be caused by missing information on variation in drainage levels, and changing management practices in farming. It is generally difficult to obtain information on the actual drainage levels and possible emission reductions achieved, as well as on farming practices. For more detailed guidance on uncertainty assessment, refer to Chapter 3, Volume 1 of the *2006 IPCC Guidelines*.

2.2.2.3 CO_2 AND NON-CO_2 EMISSIONS FROM FIRES ON DRAINED INLAND ORGANIC SOILS

Fires can be a large and variable source of greenhouse gases and significantly affect other feedbacks within the climate system. When compared to combustion of above-ground vegetation, emissions from both uncontrolled wildfires and managed (prescribed) fires in organic (peat) soils are high. On organic soils, fires comprise both surface fires that consume vegetation, litter and duff, and ground fires that burn into and below the surface. Ground fires consume soil organic matter and dead-wood mass as a fuel source. These are smouldering fires that may persist for long periods of time, burn repeatedly in response to changing soil moisture and surface hydrology, and penetrate to different depths. This section addresses emissions arising from combustion of soil organic material. Although the focus of guidance in this Chapter is on drained organic soils, the guidance in Section 2.2.2.3 could also be used to calculate emissions from fires on managed land with undrained and rewetted organic soils (Chapter 3 of this *Wetlands Supplement*).

In any ecosystem, fire activity is strongly influenced by several factors, namely weather/climate, fuel availability, drainage and ignition agents, including human activities (Johnson, 1992; Swetnam, 1993). In ecosystems with organic soils, conditions such as organic soil depth and density, soil moisture, vegetation composition and soil surface micro-topography (e.g. Benscoter & Wieder, 2003) along with fire characteristics, such as intensity, frequency and duration (Kasischke *et al*., 1995), which are affected by fire management practices, influence the quantity of organic matter consumed and hence emissions of greenhouse gases (Kuhry, 1994; Kasischke *et al*., 1995; Kasischke & Bruhwiler, 2003).

The *2006 IPCC Guidelines* cover emissions from burning of above-ground carbon stocks (biomass and dead organic matter) but do not cover the often substantial release of emissions from combustion of organic soils. It is *good practice* to report greenhouse gas emissions from fires on all managed lands with organic soils, including all fire-related emissions both from natural fires and from those that have a human-induced cause (e.g. soil drainage) even if the initiation of the fire is non-anthropogenic in nature (e.g. lightning strike).

This Chapter updates the *2006 IPCC Guidelines* by:

- providing default methodologies and emission factors for CO_2, CH_4 and CO emissions from fires on organic soils; and
- providing generic guidance for higher tier methods to estimate these fluxes.

Change in SOC following fire is the result of both CO_2 and non-CO_2 emissions (principally of CH_4 and CO). Emissions of both CO_2 and non-CO_2 greenhouse gases are addressed in the following sections. These deal specifically with below-ground biomass as opposed to vegetation and litter losses (the latter are included in the estimation of carbon stock changes in the *2006 IPCC Guidelines*).

CHOICE OF METHOD

CO_2 and non-CO_2 emissions from burning of drained organic soils can either be directly measured or estimated using data on the area burnt along with default values for mass of fuel consumed and emission factors provided in this Chapter. Previous *IPCC Guidelines* noted that emissions from wildfires on managed (and unmanaged) land can exhibit large inter-annual variations that may be driven either by natural causes (e.g. climate cycles, random variation in lightning ignitions), or by indirect and direct human causes (e.g. prescribed burning, historical fire suppression and past forest harvest activities) or by a combination of all three causes, the effects of which cannot be readily separated. This variability is also true for emissions from fires on organic soils that critically depend on extent and depth of organic soil, fuel moisture, water table depth and hence thickness of the drained layer, and resulting depth of consumed organics, all of which are affected by site characteristics, weather, land management, fire type and climate. At Tier 1, differentiation by land-management category and fire type is possible, but reporting at higher tiers will enable a greater level of differentiation between land use, site characteristics and fire types.

The parameters required to calculate the CO_2 and non-CO_2 emissions from burning organic soils are area burnt, mass of fuel available for consumption, combustion factor (also known as burning efficiency and can be used to characterise smouldering vs. flaming fires), and emission factor. Compared with vegetation fires, the uncertainties involved in estimating emissions from fires on organic soils are much higher because organic soils can burn repeatedly and to different depths. Furthermore, the type and density of the soil organic material combined with the combustion efficiency will determine the nature of gases and other compounds emitted.

The mass of fuel that can potentially burn in a fire event on organic soils will be determined by measuring the depth of burn, along with soil bulk density and carbon content; the former is strongly controlled by soil water content (influenced by position of the water table or permafrost depth) while the latter variables are ideally measured in the field. While default values can be used for Tier 1 reporting, data on the depth of burn and soil carbon density need to be determined in the case of higher tiers. The combustion factor describes how much of the fuel mass available is actually consumed during a fire event, i.e. converted into CO_2 or non-CO_2 gases. The emission factor (G_{ef}) determines the mass of CO_2 or non-CO_2 gas emitted per unit mass of fuel consumed by the fire (e.g. g CO_2/kg dry fuel). Total emissions of CO_2 or non-CO_2 gases are calculated from the product of area burnt and the corresponding biomass loading, combustion factor and emission factor.

EQUATION 2.8
ANNUAL CO_2-C AND NON-CO_2 EMISSIONS FROM ORGANIC SOIL FIRE

$$L_{fire} = A \bullet M_B \bullet C_f \bullet G_{ef} \bullet 10^{-3}$$

Where:

L_{fire} = amount of CO_2 or non-CO_2 emissions, e.g. CH_4 from fire, tonnes

A = total area burnt annually, ha

M_B = mass of fuel available for combustion, tonnes ha^{-1} (i.e. mass of dry organic soil fuel) (default values in Table 2.6; units differ by gas species)

C_f = combustion factor, dimensionless

G_{ef} = emission factor for each gas, g kg^{-1} dry matter burnt (default values in Table 2.7)

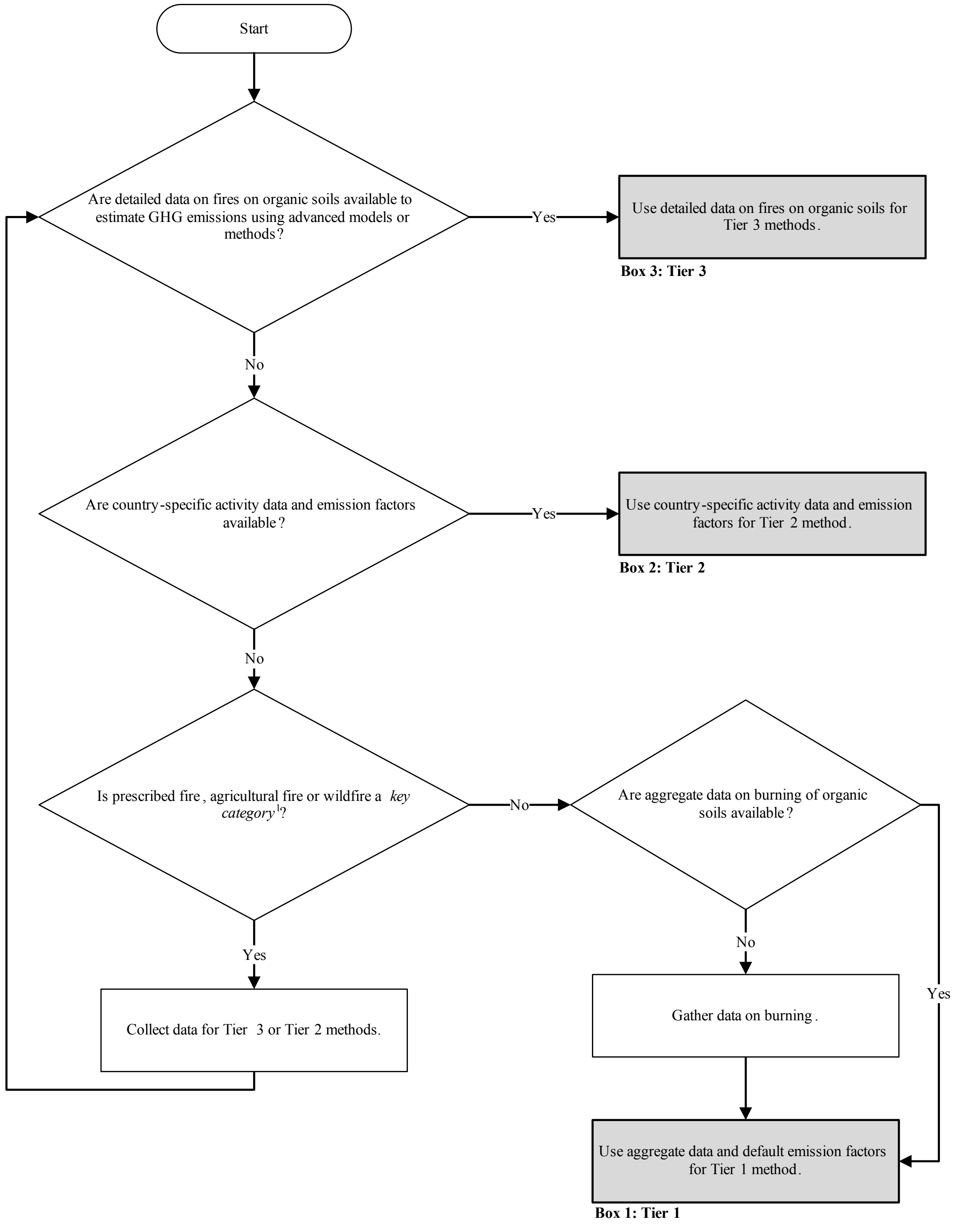
Where data for M_B and C_f are not available, a default value for the amount of fuel actually burnt (the product of M_B and C_f) can be used under Tier 1 methodology (Table 2.6). The value 10^{-3} converts L_{fire} to tonnes.

The amount of fuel that can be burnt is given by the area burnt annually and the mass of fuel available in that area.

Default values for the Tier 1 method or components of a Tier 2 method are provided in Tables 2.6 and 2.7. For higher tiers, data on the variation in the mass of fuel available (based on site- or region-specific data, including area of organic soil burnt, depth of organic soil, depth of burn and/or depth of water table/soil moisture content values and soil bulk density) are incorporated.

Figure 2.2 presents a decision tree that guides the selection of the appropriate tier level to report CO_2 and non-CO_2 emissions from the burning of organic soils.

Figure 2.2 Generic decision tree for identification of the appropriate tier to estimate greenhouse gas emissions from fires on organic soils



Note:

1: See Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), Volume 1 of the *2006 IPCC Guidelines* for discussion of *key categories* and use of decision trees.

Tier 1

Countries may choose to report CO_2 emissions using the Tier 1 method if fires on organic soils are not a *key category*. This approach is based on highly aggregated data and default factors. It does, however, require primary data on the area burnt.

If burning in ecosystems with organic soils is a *key category*, countries are encouraged to report emissions by applying the highest tier possible, given national circumstances. For prescribed fires, country-specific data will be required to generate reliable estimates of emissions.

At Tier 1, it is assumed that there is either no or very little combustive loss of soil organic matter during prescribed fires on organic soils.

Tiers 2 and 3

The Tier 1 method is refined by incorporating more disaggregated area estimates (per organic soil and fire type sub-categories) and country-specific estimates of combustion and emission factors into Equation 2.8. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Potential improvements to the Tier 1 approach may include:

- knowledge of the amount of soil organic matter consumed;
- the position of the soil water table relative to the surface;
- improved information on land use/management and their effects on organic soil condition, in particular hydrological status;
- improved data on area burnt, estimated using remotely sensed data of adequate spatial and temporal resolutions and verified according to a robust sampling design at suitable periodicity to take account of the monthly variations in area burnt; and
- estimates of the depth of burn in a representative number of locations.

Countries may further stratify the data on area burnt by depth of burn, organic soil condition (e.g. drained vs. undrained, with further detail possible through characterisation of the intensity of drainage), and fire type (wildfire vs. prescribed).

It may also be possible to develop models with algorithms to generate regional-scale maps of area burnt using satellite data from multiple sources and of moderate spatial resolution. Model results should be validated, for example, by using high spatial resolution data augmented by field observations, and refined based on validation results whenever possible. A sampling approach can be designed to generate estimates of area burnt. This reporting method should provide estimates (fluxes) of the impact of burning on below-ground biomass, particularly including the depth of burn and, if feasible, the variation of depth within the area burnt. Reporting at higher tiers should differentiate fires burning at different intensities (critical for Tier 3) and with different proportions of smouldering vs. flaming combustion (i.e. different Modified Combustion Efficiency (MCE) defined as $\Delta CO_2/(\Delta CO_2 + \Delta CO)$, which is an index of the relative proportion of smouldering vs. flaming combustion). The development of robust methodologies to assess burn severity in organic soils would enable more accurate quantification of greenhouse gas emissions from below-ground fires.

CHOICE OF EMISSION FACTORS

Tier 1

The Tier 1 method uses default values for M_B, C_f and G_{ef} along with default emission factors provided in Tables 2.6 and 2.7. Gas species in Table 2.7 are given as CO_2-C, CO and CH_4.

Due to limited data available in the scientific literature, organic soils have been very broadly stratified according to climate domain (boreal/temperate and tropical) and fire type (wild vs. prescribed). Values are derived from the literature for all categories with the exception of prescribed fires.

For all organic soil fires, the default combustion factor is 1.0, since the assumption is that all fuel is combusted (Yokelson *et al*., 1997).

TABLE 2.6
ORGANIC SOIL FUEL CONSUMPTION VALUES
(MASS OF DRY MATTER FOR A RANGE OF ORGANIC SOIL AND FIRE TYPES, TO BE USED IN CONJUNCTION WITH EQUATION 2.8, TO ESTIMATE THE PRODUCT OF QUANTITIES M_B AND C_F)

Climate/vegetation zone	Sub-category	Mean (t d.m. ha^{-1})	95% confidence interval (t d.m. ha^{-1})		Citations
Boreal/temperate	Wildfire (undrained peat)	66	46	86	Amiro *et al.*, 2001; Benscoter & Wieder, 2003; Cahoon *et al.*, 1994; de Groot & Alexander, 1986; Kajii *et al.*, 2002; Kasischke & Bruhwiler, 2003; Kasischke *et al.*, 1995; Kuhry, 1994; Pitkänen *et al.*, 1999; Poulter *et al.*, 2006; Turetsky & Wieder, 2001; Turetsky *et al.*, 2011*a*, *b*; Zoltai *et al.*, 1998
	Wildfire (drained peat)	336	4[a]		Turetsky *et al.*, 2011*b*
	Prescribed fire (land management)	-	-		No literature found
Tropical	Wildfire (undrained peat)	-	-		No literature found
	Wildfire (drained peat)	353	170	536	Ballhorn *et al.*, 2009; Page *et al.*, 2002; Usup *et al.*, 2004
	Prescribed fire (agricultural land management)[b]	155	82	228	Saharjo & Munoz, 2005; Saharjo & Nurhayati, 2005

[a] Standard error

[b] The consumption value excludes crop residues.

Note: Where fuel consumption values have been reported as t C ha^{-1}, default values for organic soil bulk density (0.1 g cm^{-3})[c] and carbon density (50% mass dry weight)[d] have been applied to derive a value for mass of fuel (t ha^{-1}) (following Akagi *et al.*, 2011). At higher tier levels, country- or ecosystem-specific values for both these variables are used.

[c] The value for surface organic soil bulk density is an average derived from Gorham (1991), who provides a default value of 0.112 g cm^{-3} for all northern peatlands and Page *et al.* (2011), who provide a default value of 0.09 g cm^{-3} for all tropical peats.

[d] The value for surface organic soil carbon content is an average derived from the typical average for eutrophic peat of 48% and the typical average for oligotrophic peat of 52% (after Lucas (1982), Immirzi *et al.* (1992) as reported in Charman (2002)).

TABLE 2.7
EMISSION FACTORS (G KG^{-1} DRY MATTER BURNT) FOR ORGANIC SOIL FIRES. VALUES ARE MEANS ± 95% CI (TO BE USED AS QUANTITY G_{EF} IN EQUATION 2.8)

Climate/vegetation zone	CO_2-C	CO	CH_4	Citations
Boreal/temperate	362 ± 41	207 ± 70	9 ± 4	Ward & Hardy, 1984; Yokelson *et al.*, 1997; Yokelson *et al.*, 2013
Tropical	464	210	21	Christian *et al.*, 2003

1. These values have been derived from a very limited number of studies. The EF values for boreal/temperate fires are arithmetic means of the two values reported by Yokelson *et al.* (1997) for Alaska and Minnesota organic soils (carbon content 49% for Minnesota; n.d. for Alaska), of the minimum and maximum values reported by Ward and Hardy (1984) (no carbon contents reported) and of the single value reported by Yokelson *et al.* (2013) for Alaskan organic soil (carbon content 42%). Surface (flaming) and deep (smouldering) organic soil fires produce a complex mixture of gases and fine particles, the nature of which will reflect vegetation type, fire behaviour, soil physical and chemical characteristics as well as combustion conditions (in particular combustion efficiency) (Itkonen & Jantunen, 1986; NCDENR, 1998). The combustion of organic material leads to a loss of carbon; most of this is in the form of CO_2, but quantities of CO, CH_4, long-chain hydrocarbons and carbon particulate matter are also emitted. Other greenhouse gases along with ozone precursors (NO_x), volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons are also released (Ramadan *et al.*, 2000; Gebhart *et al.*, 2001; Honrath *et al.*, 2004; Val Martin *et al.*, 2006; Lapina *et al.*, 2008; Akagi *et al.*, 2011). Emission factors for N_2O and NO_x are not provided at Tier 1. There are very limited data for N_2O and NO_x emissions from organic soil fires and it should be noted that N_2O can be produced in canisters during sample storage (e.g. Cofer *et al.*, 1990). At higher tiers, N_2O and NO_x can either be measured directly or could be calculated using published emission ratios for organic soil fires (e.g. Christian *et al.*, 2003; Hamada *et al.*, 2013).
2. The composition of organic soil fire emissions differs substantially from forest fires on mineral soils; in part, this is a function of the fact that organic soil fires are dominated by smouldering rather than flaming combustion owing to the moist and often oxygen-limiting substrate conditions. Fire temperatures also differ: the typical peak temperature of smouldering organic soil fires is in the range 500–700°C, while for flaming fires it can be 1000–1500°C (Usup *et al.*, 2004; Rein *et al.*, 2008). The lower temperatures and smouldering combustion associated with organic soil fires make them harder to detect by satellites and lead to the emission of high amounts of CO relative to CO_2 as well as large amounts of fine particulate matter (PM2.5); fires on tropical organic soils, for example, emit as much as three to six times more particulate matter per amount of biomass consumed than other types of biomass fires (grassland, forest, plantation fires) (Heil *et al.*, 2006). The emission ratio of CO to CO_2 ($ER_{CO/CO2}$) can be used as an indicator of the relative amount of flaming versus smouldering combustion during biomass burning with higher $ER_{CO/CO2}$ observed in smouldering fires (Cofer *et al.*, 1989, 1990; Christian *et al.*, 2007; Yokelson *et al.*, 2007).

Tiers 2 and 3

At higher tiers, the approach for estimating greenhouse gas emissions from fires on organic soils incorporates country-specific information into Equation 2.8. When deriving higher tier emission factors, country-specific combustion factors need to be developed. Regional factors for stratification could include:

- stratification by drainage class - position of the soil water table is a proxy for soil moisture, which determines depth of burn;
- stratification by depth of burn - this can be measured in the field post-fire (e.g. Turetsky & Wieder, 2001; Page *et al.*, 2002; Turetsky *et al.*, 2011*a*) or using remote sensing approaches (e.g. LiDAR) (Ballhorn *et al.*, 2009);
- stratification by fire type (wild vs. prescribed fires) - GIS techniques of interpolation may be helpful in this analysis; under Tier 3, one might consider annual sampling of a number of control sites;
- stratification by organic soil type taking into account general hydrology (e.g. bog vs. fen) and vegetation structure (open, shrubby, forested) whenever possible;
- use of regionally specific values for organic soil bulk density and carbon concentration; and
- stratification by land-use and management types, including differences in drainage layout and intensity, land-use intensity and practices, all of which will influence the mass of fuel available for combustion.

Emission factors can be derived from measurements (field or laboratory-based) or calculations validated against country-specific measurements. The literature on emissions from fires on organic soils is very sparse and countries are encouraged to share data when organic soil quality, environmental conditions, and land-use practices are similar.

A higher tier approach might also use process-based models, adequately validated using observation data that take into account temporal and spatial variations in the differences between fires on different types of organic soils and conditions and fuel combustion efficiencies. This approach will involve a comprehensive mechanistic understanding of combustion of organic soils, including the effects of site characteristics, drainage intensity, vegetation cover, soil type and depth, management practices, depth of water table and soil moisture, among others. Higher tier approaches could start by developing robust relationships between drainage and depth of burn, which could then be further refined by land-management category. Models ideally also take into account the fire return interval. Fire changes organic soil chemical and physical characteristics (Yefremova & Yefremov, 1996; Zoltai *et al*., 1998; Milner *et al*., forthcoming) as well as the rate and nature of post-fire vegetation recovery, and thus can alter total net ecosystem productivity.

CHOICE OF ACTIVITY DATA

Activity data consist of areas of land remaining in a land-use category with organic soils stratified by climate zone and fire type. Total areas should be determined according to the Approaches laid out in Chapter 3, Volume 4 of the *2006 IPCC Guidelines* and should be consistent with those reported under other sections of the inventory. The assessment of fire-driven changes in soil carbon will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, maps of burnt area, and other biophysical data. Stratification of land-use categories according to climate zones, based on default or country-specific classifications, can be accomplished with overlays of land use on suitable climate and soil maps.

Tier 1

The Tier 1 method requires data on burnt area of organic soils stratified by climate domain and fire type (wild vs. prescribed). Data on burnt area can be obtained from ground-based inventories, which can be very valuable in areas of small fire. Some countries/regions may have an established fire inventory method in place, which they are encouraged to maintain rather than go with less comprehensive satellite methods. For larger and/or less accessible locations, burnt area data are often obtained from a time series of images from remote sensors. In-country burnt area maps should ideally be mapped at Landsat TM scale (30–50 m resolution). If data not available at this resolution, 250 m and even 1 km data can be used. Box 2.1 provides more details on the remote sensing platforms currently used for obtaining burnt area data. Other methods, such as national statistics and forest inventory fire data, can also produce suitable information in some cases, but may not be as reliable or as comprehensive as remotely sensed data. Caution is advised regarding the detection of thermal anomalies using datasets derived from satellite data. Although this provides a reasonable indicator of the presence of a fire, burnt area parameters required in the emission estimate equations cannot reliably be derived.

BOX 2.1
RECENT ADVANCES IN SATELLITE-DERIVED FIRE PRODUCTS

Recent advances in satellite-derived fire products using MODerate resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites (Roy *et al*., 2008; Giglio *et al*., 2009), the Advanced Very High Resolution Radiometer (AVHRR) sensor of the National Oceanic and Atmospheric Administration (NOAA), Polar Operation Environmental Satellite (POES), the European AATSR and VEGETATION/PROBA satellites, and the Geostationary Operational Environmental Satellite (GOES) have all enabled the derivation of burnt area data in near real-time and thereby enhanced the ability to estimate the areal extent of regional and global wildfires and hence the scale of emissions (e.g. Gregoire *et al*., 2003; Simon *et al*., 2004; Tansey *et al*., 2008; Giglio *et al*., 2009; Kasischke *et al*., 2011). Products derived from the satellite datasets provide either an indication of the area burnt or an indication that a possible active fire is burning within the grid cell, based on a high surface temperature signal at thermal wavelengths. At the global scale, these datasets are coarse resolution (a pixel size larger than 500 m). The resulting uncertainties and particular challenges associated with commission and omission errors in remote sensing approaches to peat fire detection and characterisation, however, need to be recognised and acknowledged. In normal years, for example, fires on tropical organic soils are relatively small (several hectares would be towards the upper end), and it is therefore necessary to consider using satellite datasets acquiring imagery at an appropriate resolution. During extended smouldering, fires in organic soils may be particularly difficult to pick up by sensors sensitive to thermal wavelengths. There are ongoing issues with cloud cover, which are being addressed with increasing use of radar imagery. Furthermore, there are very few operational systems that can be used to develop robust and temporally stable products. The Landsat-8 mission and the forthcoming European Space Agency/European Commission Sentinel programme will help address this issue. The size of the study area is also very important as there may be existing datasets available from which a long-term time series of fire disturbance can be reconstructed (e.g. 40 years of Landsat data with gap filling with radar imagery). The UN World Meteorological Organization has produced useful materials on fire assessment and standards (e.g. GTOS-68, 2009).

Data on the location of organic soils can be obtained from several institutions, including ISRIC and FAO, which have country-specific and global maps that include organic soils (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/;

http://www.fao.org/geonetwork/srv/en/main.home; http://www.isric.org/). A global consortium has been formed to make a new fine resolution digital soil map of the world (http://www.globalsoilmap.net/).

Tiers 2 and 3

Higher tier methods require more disaggregated and spatially explicit activity data than lower tiers. This includes disaggregation according to drainage class, vegetation type and condition (the latter refers to moisture, leaf on/off, and other factors), drainage depth, and land-management status to improve Tier 1 estimates. It may also take into account such variables as seasonal norms and modifications in water table level due to seasonal weather patterns, etc. Data on depth of burn (obtained from *in situ* field measurements), along with country-specific data on organic soil bulk density and carbon content, will also greatly improve knowledge of the mass of fuel consumed and the scale of carbon emissions. Seasonal variations in fire-driven emissions are then aggregated to annual emissions.

The accuracy of emission estimates will be further improved if information is available on land use and its effect on organic soil condition, since fire extent and severity and hence quantity of emissions increase according to the scale of disturbance (e.g. disturbance of vegetation cover and the presence of drainage structures associated with agriculture, forestry, peat extraction, oil and gas extraction, roads etc. (e.g. Turetsky *et al.*, 2011*a*, *b*)). Remote sensing techniques (e.g. Kasischke *et al.*, 2009) can also be used to provide an indication of likely fire risk by estimating soil water conditions and providing an accurate proxy measure of organic soil surface water content levels and hence likely depth of burn at a landscape scale.

CALCULATION STEPS FOR TIER 1

The steps for estimating CO_2 and non-CO_2 emissions from fires on drained organic soils for land remaining in a land-use category are as follows:

Step 1: Using guidance in Chapter 3, Volume 4 of the *2006 IPCC Guidelines*, stratify areas with drained organic soils of land remaining in a land-use category for each land-use category according to climate domain and fire type. Obtain estimates of A (area burnt) from national sources or, if not available, from global databases.

Step 2: Assign the appropriate fuel consumption value from Table 2.6 (M_b*C_f with $C_f=1$) and emission factor (G_{ef}) from Tables 2.6 and 2.7 for the gas.

Step 3: Estimate CO_2 or non-CO_2 emissions by multiplying the burnt area by the appropriate fuel load (M_B) and emission factor (G_{ef}) from Tables 2.6 and 2.7 using Equation 2.8.

Step 4: Repeat step 3 for each greenhouse gas using emission factors (G_{ef}) in Table 2.7.

UNCERTAINTY ASSESSMENT

There are several sources of uncertainty related to estimates of CO_2 and non-CO_2 emissions from fires on organic soils. Fire behaviour varies greatly among wetland types and hence, disaggregation of vegetative formations will lead to greater precision. The fraction of fuel that is actually combusted during burning (the combustion factor) varies, not only between ecosystems, but also between fires, between years, and as a function of land-management practices. Measurements from a given fire, year and/or region cannot be extrapolated with confidence to other locations or years, or to the biome scale. An important cause of uncertainty is the choice of emission factor that partitions the smoke into CO_2, CO and other trace gases, since this is strongly driven by the amount of flaming versus smouldering combustion that occurs; this can vary widely in organic soils, and is not well characterised from field data. In addition, the accuracy of estimates of area burnt, proportion of the available fuel oxidised and the biomass fuel available also contribute to emission uncertainty. Uncertainties of estimates of areas burnt can vary markedly depending on the methodology employed; for example, where very high resolution remote sensing is used, it may be of the order of ±20%, whereas the use of global fire maps may result in uncertainties of up to two-fold. Uncertainties in estimates of greenhouse gas emissions from fire over large regions are likely to be at least ±50%, even with good country-specific data, and at least two-fold where only default data are used. The calculation of emission errors is addressed by French *et al.* (2004). The study looked at possible ranges of error in input variables, since robust data are not available for the range of fire conditions and vegetation types that can burn. The sensitivity analysis revealed that the ground-layer fraction consumed is the most important parameter in terms of output uncertainty, indicating that burning in sites with deep organic soils can be the most problematic in terms of uncertainty. The results of that work showed that input datasets are incomplete in describing the possible variability in conditions for both pre-burn and during the fire, and attention to improving measurements and obtaining a range of measurements is a priority for modelling emissions from fire in organic soils.

2.3 LAND CONVERTED TO A NEW LAND-USE CATEGORY

2.3.1 CO_2 emissions and removals from drained inland organic soils

CO_2 emissions/removals from land converted to another land-use category on drained organic soils are calculated in the same way as CO_2 emissions/removals from land remaining in a land-use category.[1] CO_2 emissions/removals for the lands in the conversion category are calculated using Equations 2.1 and 2.2.

On-site CO_2 emissions after land-use change on drained organic soils can occur from all five carbon pools. Land-use change can result in direct losses/gains because of biomass clearance/(re)planting. This is addressed by guidance for changes in the carbon pools in above-ground and below-ground biomass and dead organic matter on lands converted to another land-use category provided in the *2006 IPCC Guidelines*.

Land-use change can indirectly affect carbon gains and losses because of altered growth of woody biomass and altered respiration and organic matter oxidation through altered soil temperature. These effects are included in the guidance for lands remaining in a land-use category provided in the *2006 IPCC Guidelines* for above-ground and below-ground biomass and dead organic matter and updated emission factors in Table 2.1 in Section 2.2.1.1.

Additional carbon losses from biomass and soil can occur through altered fire frequency after drainage and land-use change. These CO_2 emissions from fire are addressed in Section 2.3.2.3.

2.3.1.1 ON-SITE CO_2 EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS ($CO_2\text{-}C_{ON\text{-}SITE}$)

CHOICE OF METHOD

Tier 1

CO_2 emissions/removals from land converted to another land-use category on drained organic soils within the inventory time period are calculated in the same way as CO_2 emissions/removals from land remaining in a land-use category. CO_2 emissions/removals for lands in the conversion category are calculated using Equation 2.3 if soils are drained. Specific guidance for other land-use categories is given in Chapters 5, 6, 8 and 9 of the *2006 IPCC Guidelines*.

At Tier 1, there is no transition period for CO_2 emissions from drained organic soils because the land immediately switches to the methods for the new land-use category. High carbon loss from drained organic soils can occur after natural vegetation is converted to another land use, e.g. after converting tropical Forest Land to palm plantations, or converting Grassland to Cropland, and in particular, immediately after initial drainage of organic soils (Stephens *et al.*, 1984; Wösten *et al.*, 1997; Hooijer *et al.*, 2012). These $CO_2\text{-}C_{on\text{-}site}$ emissions in the transition phase are not captured by the Tier 1 default emission factors shown in Table 2.1, which were derived from data representing long-term land uses present for decades in the boreal and temperate climate zones, and land uses drained for more than six years in the tropical climate zone. A transitional phase is not captured by Tier 1 methodology due to lack of scientific data for deriving default emission factors. After initial drainage of organic soils and if a transitional phase occurs, this should be addressed using higher tier methods.

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[1] For example, if Forest Land is converted to Cropland, methodology and emission factors for Cropland are to be used.

Tier 2

Country-specific Tier 2 emission factors may include CO_2 emissions in the transition phase after land conversion, in particular after initial drainage of organic soils and when land conversion is associated with deeper drainage.

Tier 3

Tier 3 methodologies could further consider the dynamic nature of the additional $CO_2\text{-}C_{\text{-on-site}}$ emissions in the transition phase, which may be highest in the first years after the transition.

Additional guidance on Tier 1, 2, and 3 approaches is given in Section 2.2.1.1.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

At Tier 1, CO_2 emission/removal factors for lands in the conversion category are the same as for land remaining in a land-use category. For Tier 1, these are given in Table 2.1. Additional guidance on Tier 1, 2, and 3 emission/removal factors is given in Section 2.2.1.1.

Tier 2

If land conversions on drained organic soils contribute significantly to CO_2 emissions from soils and if CO_2 emissions from soils are a *key category*, it is *good practice* to develop country-specific Tier 2 emission factors that include additional $CO_2\text{-}C_{\text{on-site}}$ emissions in the transition phase. Tier 2 emission factors could be stratified by type of land conversion and by the magnitude of change in water table through drainage. Unless other country-specific evidence is available, the default length of 20 years can be used for the transition phase.

Tier 3

Tier 3 methodologies could develop response functions or models that capture the dynamic nature of additional $CO_2\text{-}C_{\text{soil-onsite}}$ emissions in the transition phase.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.1.1.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.1.1.

2.3.1.2 OFF-SITE CO_2 EMISSIONS VIA WATERBORNE CARBON LOSSES FROM DRAINED INLAND ORGANIC SOILS ($CO_2\text{-}C_{\text{SOIL-ONSITE}}$)

CHOICE OF METHOD

Tier 1

At Tier 1, CO_2 emissions/removals from land converted to another land-use category on drained organic soils within the inventory time period are calculated in the same way as CO_2 emissions/removals from land remaining in a land-use category. Guidance for DOC is given in Section 2.2.1.2. CO_2 emissions/removals for lands in the conversion category are calculated using Equations 2.4 and 2.5.

Tier 2

The Tier 2 approach for waterborne carbon losses from drained organic soils incorporates country-specific information to estimate emissions. Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Tier 2 emission factors can be developed following the same principles as for land remaining in a land-use category. Guidance is given in Section 2.2.1.2. Generally, the same stratification should be used for land converted to another land-use category as is used for land remaining in a land-use category. Tier 2 approaches for land-use changes can be further stratified according to the time since land-use change. Specific transition periods can be considered depending on the type of land-use change and the persistence of emissions or removals, which differ from those on lands that have been in the new land-use category for a long time. Alternatively, the default transition period applicable to the new land-use category in the *2006 IPCC Guidelines* can be applied.

Tier 3

The development of Tier 3 approaches follows the guidance given in Section 2.2.1.2, including the guidance for transparent documentation of Tier 3 approaches given in Section 2.2.1.1. Generally, the same approach should be used for land converted to another land-use category as is used for land remaining in a land-use category. Tier 3 methods should further differentiate transition effects of increased or reduced waterborne carbon losses after land-use change and time since land-use change.

Additional guidance on Tier 1, 2, and 3 approaches is given in Section 2.2.1.2.

CHOICE OF EMISSION/REMOVAL FACTORS

CO_2 emission/removal factors for lands in the conversion category are the same as for land remaining in a land-use category. For Tier 1, these are given in Table 2.2. Additional guidance on Tier 1, 2, and 3 emission/removal factors is given in Section 2.2.1.2.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.1.2.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.1.2.

2.3.2 Non-CO_2 emissions and removals from drained inland organic soils

2.3.2.1 CH_4 EMISSIONS/REMOVALS FROM DRAINED INLAND ORGANIC SOILS

CHOICE OF METHOD

CH_4 emissions/removals from land converted to another land-use category on drained organic soils within the inventory time period are calculated in the same way as CH_4 emissions/removals from land remaining in a land-use category.[2] CH_4 emissions/removals for lands in the conversion category are calculated using Equation 2.5. Additional guidance on the Tier 1, 2, and 3 approaches is given in Section 2.2.2.1.

CHOICE OF EMISSION/REMOVAL FACTORS

CH_4 emission/removal factors for land in the conversion category are the same as for land remaining in a land-use category. For Tier 1, these are given in Tables 2.3 and 2.4. Additional guidance on Tier 1, 2, and 3 emission/removal factors is given in Section 2.2.2.1.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.1.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.1.

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[2] For example, if Forest Land is converted to Cropland, methodology and emission factors for Cropland are to be used.

2.3.2.2 N_2O EMISSIONS FROM DRAINED INLAND ORGANIC SOILS

CHOICE OF METHOD

N_2O emissions from land converted to another land-use category on drained organic soils within the inventory time period are calculated in the same way as N_2O emissions from land remaining in a land-use category. N_2O emissions for lands in the conversion category are calculated using Equation 2.7. Additional guidance on Tier 1, 2, and 3 approaches is given in Section 2.2.2.2.

CHOICE OF EMISSION/REMOVAL FACTORS

N_2O emission factors for land in the conversion category are the same as for land remaining in a land-use category. For Tier 1, these are given in Table 2.5. Additional guidance on Tier 1, 2, and 3 emission/removal factors is given in Section 2.2.2.2.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.2.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.2.

2.3.2.3 NON-CO_2 EMISSIONS FROM BURNING ON DRAINED ORGANIC SOILS

CHOICE OF EMISSION/REMOVAL FACTORS

Non-CO_2 emission factors for land in the conversion category are the same as for land remaining in a land-use category. For Tier 1, these are given in Tables 2.6 and 2.7. Additional guidance on Tier 1, 2, and 3 emission/removal factors is given in Section 2.2.2.3.

CHOICE OF ACTIVITY DATA

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.3.

UNCERTAINTY ASSESSMENT

Guidance is the same as for land remaining in a land-use category, as given in Section 2.2.2.3.

2.4 COMPLETENESS, TIME SERIES CONSISTENCY, QA/QC AND REPORTING AND DOCUMENTATION

2.4.1 Completeness

Complete greenhouse gas inventories will include estimates of all greenhouse gas emissions and removals on drained inland organic soils for which Tier 1 guidance is provided in this Chapter, for all types of organic soils and land-use categories that occur on the national territory. Further guidance on completeness is provided in Chapter 7.5 of the *Wetlands Supplement.*

2.4.2 Time series consistency

It is *good practice* for countries to clearly define organic soils and use this definition consistently over time.

Consistent time series require that the same methodology be used for the entire time series. Whenever new methodologies are used, previous estimates should be recalculated using the new methods for all years in the time series. It is also *good practice* to report why new estimates are regarded as more accurate or less uncertain.

One potential problem in recalculating previous estimates is that certain datasets may not be available for the earlier years. There are several ways of overcoming this limitation and they are explained in detail in Chapter 5, Volume 1 of the *2006 IPCC Guidelines*. Time series consistency is discussed further in Chapter 7.6 of the

Wetlands Supplement and Chapter 5, Volume 1 (Time series consistency and recalculations) of the *2006 IPCC Guidelines*.

2.4.3 Quality Assurance and Quality Control

It is *good practice* to develop and implement quality assurance/quality control (QA/QC) procedures as outlined in Chapter 7.7 of the *Wetlands Supplement*. Countries using Tier 1 methods are encouraged to critically assess the applicability of default assumptions to their national circumstances. These default assumptions are presented in the main text and Annexes to this Chapter. Water table or drainage classes and time after water table drawdown are likely to have the strongest impact on greenhouse gas emissions and removals. Water table information should be factored in to the assessment of the applicability of or development of emission factors. Countries are encouraged to focus the efforts of QA/QC procedures on the accuracy of water table information.

Higher tier methods should be carefully designed to ensure that resulting estimates are compatible across different pools. In particular, potential double-counting or omission of emissions or removals could occur if measurements underlying national emission factors comprise several carbon pools, e.g. organic soil pool and dead organic matter, soil respiration with components of autotrophic and heterotrophic respiration that are not attributable to the organic soil, or combined on-site and off-site CO_2 emissions. Annex 2A.1 of this Chapter describes the underlying assumptions and methodologies used in deriving Tier 1 emission factors that avoid double-counting or omission of carbon pools.

Where country-specific emission factors are used, they should be based on high-quality field data, developed using a rigorous measurement programme and adequately documented, preferably in peer-reviewed, scientific literature.

It is *good practice* to develop additional, category-specific QA/QC procedures for greenhouse gas emissions and removals from drained organic soils. Examples of such procedures include, but are not limited to, examining the time series of the total area of managed land on organic soils and the fraction of these soils that is drained across all land-use categories (to ensure there are no unexplained gains or losses of land) and conducting a comparative analysis of emission factors in the scientific literature or in neighbouring countries with similar environmental and management conditions.

2.4.4 Reporting and documentation

Chapter 7.2.1.1 of the *Wetlands Supplement* provides specific guidance on where to report greenhouse gas emissions and removals from drained organic soils.

It is *good practice* for countries to report and document how they define organic soils, how they ensure consistency with the IPCC definition and how drained organic soils are identified.

Countries using Tier 1 methods are encouraged to document their assessment of whether the default assumptions are applicable to their national circumstances and of actions taken in case default assumptions are considered not or only partially applicable. It is *good practice* to document how national data compare to default assumptions and why they may differ. Whenever national methodologies are used it is *good practice* to document transparently and completely data sources, underlying assumptions, compatibility with the assumptions in the Tier 1 methodology or reasons for deviations, data used, and models or calculation algorithms used in the national methodology. It is *good practice* to document, and countries are encouraged to publish, the data, methodology and results of their assessment of how and why they represented the national circumstances and to document the QA/QC procedures, e.g. peer-review of methodologies before application in the inventory.

Annex 2A.1 Scientific background for developing CO_2-C emission/removal factors for drained inland organic soil from the scientific literature in Table 2.1

The Tier 1 CO_2 emission factors presented in Table 2.1 were calculated as annual net change of soil organic carbon (SOC) plus below-ground portion of litter carbon in different land uses. CO_2 emissions were obtained using two well-established methodologies:

1. **Flux method:** Flux measurements are commonly used on all types of organic soils to determine gas exchange at frequencies from minutes to weeks over monitoring periods of up to a few years.
2. **Subsidence method:** Determining subsidence rates of drained organic soils at frequencies of months to years, over periods representing one to many years of subsidence.

Flux method

The flux method uses chamber-based techniques or eddy covariance in combination with auxiliary carbon pool data from the study sites.

Dark chamber measurements

Chamber flux measurements are made with varying frequency over short periods with dark chambers to determine total respiration (Rt), which includes autotrophic (Ra) plus heterotrophic (Rh) respiration from the soil and heterotrophic respiration from litter. To obtain organic soil CO_2 emissions, the observed flux (Rt) must be adjusted for contributions from other carbon pools (e.g. litter) and autotrophic (plant root) respiration needs to be subtracted (Ojanen *et al.*, 2012). For these calculations, the proportion of Rh to Rt was estimated from a limited number of studies.

As with any mass balance approach, outputs must be balanced against inputs to calculate a net flux to the atmosphere. Thus, inputs in the form of root mortality and above-ground litterfall are important in calculating net carbon loss or gain. Tier 1 assumes that the litter pool remains constant in land remaining in a land-use category, so litter inputs to SOC are equal to litterfall plus root mortality. While litterfall is relatively easy to measure, below-ground litter inputs are hard to measure directly (Gaudinski *et al.*, 2010; Finér *et al.*, 2011; Sah *et al.*, 2011). Estimates of litter inputs were made from a limited number of studies and were subtracted from Rh to estimate the net flux of carbon to the atmosphere. On Peatlands Managed for Extraction, no vegetation is present and so the net change in soil carbon was assumed to be Rh.

Transparent chamber measurements

CO_2 emission measurements using transparent chambers determine net ecosystem exchange (NEE), i.e. the balance between Rt and gross primary productivity (GPP). To obtain SOC emissions, NEE must be corrected for the contributions from other carbon pools (e.g. litter, above-ground biomass, etc.). Design and use of transparent chambers are described in detail by Drösler (2005).

Eddy covariance flux measurements

The eddy covariance (EC) method is the most useful for larger sites or at landscape scales. Sophisticated instrumentation and data-processing software calculate fluxes of gases by the covariance of gas concentrations with upward and downward movements of air parcels. In its simplest interpretation for CO_2 fluxes, the EC method measures NEE (the balance of ecosystem respiration and GPP). Whenever photosynthetically active radiation (PAR) is zero (such as at night), GPP is zero and NEE is equivalent to ecosystem respiration or Rt. In essence, the strategy for obtaining Rh from EC results is the same as for transparent chambers; correction is required for Ra (above-ground and below-ground), removals of biomass carbon, inputs of carbon from fertilisers, etc.

Subsidence method

Drainage of an organic soil leads to subsidence or loss of elevation (Armentano & Menges, 1986; Grønlund *et al.*, 2008; Leifeld *et al.*, 2011). Oxidative loss of carbon can be related to volume loss of the organic soil using bulk density and soil carbon content obtained from soil cores or pits. Total subsidence of the drained organic soil surface is tracked over time using elevation markers. Other markers, such as pollen, have been used to correlate horizons among cores (Minkkinen *et al.*, 1999) as an aid to determining subsidence rates.

The parameters used for calculating emissions in each study varied slightly. We applied a standardised approach to calculating emissions from each study so that assumptions across sites would be consistent. CO_2 emission estimates are obtained by converting the volume loss to carbon via bulk density, carbon content and estimates of the oxidised fraction of the volume lost compared with compaction. Bulk density was considered to remain constant over short periods of time and oxidation fractions were calculated from data in each paper, when available, or data from similar sites were used when data were not available. In all papers in tropical climate, carbon content was measured by loss on ignition, which may lead to an underestimate of the carbon content. For these studies, carbon content was estimated using the relationship of Warren *et al.* (2012). Subsidence emissions were corrected for DOC losses using Tier 1 default factors from Section 2.2.1.2.

Tropical emission/removal factors

Two types of data were available for the tropical climate zone: flux studies and studies based on subsidence. Integrating the two approaches was problematic because the data for each approach were different and because many studies had not measured all parameters required to fully assess C losses. The approach that was finally adopted was to calculate one estimate using a gain-loss approach based on flux data for each of the gain and loss terms of the mass balance for each land use. A second estimate was calculated using the subsidence approach, aggregated by site. The average of the two approaches was used to determine the emission factor, when there were appropriate data available for a particular land use. This was only the case for acacia and oil palm plantations.

There was divergence of opinion on several points with regard to each of the calculations described above; the general approach adopted was to calculate independent estimates using different best judgements about the application of subsidence and gain-loss calculations to the dataset and to then average the two calculations when they came to different values. One point of divergence was over the importance of consolidation of peat layers below the water table. Another was over the ability of surface flux measurements to adequately capture respiration of below-ground litter. Two calculations were made, one excluding one recently cleared subsidence site and including the below-ground carbon inputs to the measured surface fluxes. A second calculation was made including the site previously excluded and excluding below-ground inputs. The final emission factor was derived from the average of these two calculations.

Errors were propagated using the quadrature of absolute errors method (Malhi *et al.*, 2009) for each calculation. Most estimates converged, but several estimates differed by more than 4 tonnes C $ha^{-1}yr^{-1}$. These differences were not statistically significant and means from each approach were within the 95% confidence interval of each other. To resolve the discrepancy between the two approaches, the final emission factor was determined to be the mean of the two approaches. The uncertainty interval was taken from the highest and lowest values of the 95% confidence interval for either approach.

Selection of studies

A dramatic increase in published studies of CO_2 fluxes occurred recently but not all studies reported results that could be used to develop Table 2.1. Studies included in the derivation of emission factors were assessed on the basis of a set of quality criteria.

- Study site characteristics (site location, land use, soil type, peat depth, land-use history prior to current land use described, and water table). Sites on drained organic soils were included. All sites in the boreal and temperate zone had a decadal history of reported land use. Sites in tropical climate had at least six years of drainage and current land use.
- Experimental study design: need for exclusion of unrealistic data, e.g. extreme fertilisation, extreme water table level. Only “control” and common practice sites were included. Many experimental studies involved manipulations other than drainage so often their results could not be used; exceptions are results from a “control” drained site. Survey studies, particularly on Cropland and Grassland, often involved fertilisation or annual cropping where corrections were often possible to determine Rh. Most studies in the boreal climate region and many in the temperate were conducted seasonally, typically from April/May through September/October (in the northern hemisphere). Annualisation of seasonal results was guided by several studies that specifically targeted winter fluxes (e.g. Alm *et al.*, 1999; Heikkinen *et al.*, 2002; Saarnio *et al.*, 2007). Tropical sites were assessed as representative of the annual flux 1) if data adequately covered dry and wet seasons, in practice seven months or more; and 2) if there were at least monthly flux observations (typically more in short studies).
- Monitoring and flux quality (study design and position of chambers and subsidence poles, temporal coverage, spatial coverage, monitoring frequency, total number of samples, number of replicates, measurement methodology, methodology used for annual flux estimates, data quality control, and uncertainty estimate for fluxes provided). Studies were accepted if there were at least three spatial replicates. Studies in tropical climate were additionally ranked from “A” = “very good and robust” to “E” = “highly uncertain, inadequate for deriving annual emission factors”. Studies classified from A to D were included in the derivation of emission factors to use the broadest possible database despite sometimes there being considerable uncertainty.

- Every site was entered as one entry into the emission factor data. Multi-year observations were averaged to a single value to avoid over-representation of sites with a long time series of observations.
- Transparency and traceability of reported values and calculations: in the case of studies with incomplete methodology description or inconsistent reported numbers, the authors of the assessed studies were contacted. This made it possible to reduce uncertainty in a few studies. Unclear studies were excluded.
- No double-counting: some studies were performed close to each other. Authors who knew the exact positions of the observation points were contacted to check whether observations were independent of each other. Sites located within a few metres of each other were treated as one. Some of the subsidence studies had large numbers of replicates, which may be partially independent of each other. There was no agreement among the authors on how to objectively split these studies into sub-sites, so each subsidence study was treated as a single site.
- Criteria for gain and loss terms of mass balance for the flux method: some studies using the flux method, including most studies in tropical climate, have reported total soil respiration only. In these cases, the reported CO_2 flux had to be corrected by gain and loss terms of mass balance to derive the CO_2 flux from the organic soil pool in Table 2.1 and to avoid double-counting with biomass and litter carbon pools. These terms are the ratio of heterotrophic to total respiration, above-ground litter input and fine root mortality (Hergoualc'h & Verchot, 2013). Whenever available, the terms were taken directly from the flux studies. Otherwise, generic land-use-specific values were developed based on studies of these terms that passed the quality criteria of study site characteristics, monitoring quality, transparency, and traceability. The ratio of heterotrophic to total respiration data was derived purely from studies on organic soils. When no data were available, e.g. for sago palm plantations and rice, the ratio was transferred from the most similar land-use type. Above-ground litter and root input were available from studies on organic soils for all land-use types except for plantations and rice. Instead of *Acacia crassicarpa*, which is grown on organic soils, data from *Acacia mangium* chronosequences on mineral soils (Nouvellon *et al*., 2012) were used, which best reflected the age-dependent litter production. For oil palm, data from mineral and organic soils were used (Henson & Dolmat, 2003; Lamade & Bouillet, 2005). Due to high root biomass and spatial heterogeneity (Dariah *et al*., 2013), root input by oil palm is particularly uncertain. For sago palm, the oil palm and rice values were used for above-ground and below-ground inputs, respectively, due to lack of land-use-specific data (Kakuda *et al*., 2005).

Annex 2A.2 Derivation of ditch CH_4 emission factors

The Tier 1 default emission factors presented in Table 2A.1 were derived from the published studies listed. The number of studies available remains relatively small, although some include a substantial number of individual measurement sites. Measured fluxes are generally quite variable within each soil/land-use type, and are not evenly distributed across different organic soil types (e.g. most of the data for deep-drained and shallow-drained Grassland on organic soils are obtained from studies in the Netherlands). Tier 1 defaults for $EF_{CH4\text{-}ditch}$ were derived from the mean of all data within each land-use class, and uncertainty ranges were calculated as 95% confidence intervals. Indicative Tier 1 default values for the fractional area of ditches within drained organic soils were calculated in the same way, except that data from the Netherlands were omitted from the Grassland classes, on the basis that fractional ditch areas are considered to be higher in that country than elsewhere, and that their inclusion would therefore lead to atypically high default values. Note that there are currently few data on CH_4 emissions from ditches in tropical organic soils or from blanket bogs. Further published data on ditch CH_4 emissions may be used to refine the default values presented in Table 2.4, or to derive country-specific Tier 2 emission factors.

TABLE 2A.1
COLLATED DATA ON DITCH CH_4 EMISSIONS FROM DRAINED AND REWETTED ORGANIC SOILS

Organic soil/land-use type	**Country**	**Reference**	**EF_{CH4_ditch} ($t\ CH_4\text{-}C\ ha^{-1} yr^{-1}$)**	**$Frac_{ditch}$**
Deep-drained Grassland	The Netherlands	Schrier-Uijl *et al.*, 2010*b*, 2011	0.435	0.21
Deep-drained Grassland	The Netherlands	Vermaat *et al.*, 2011	0.592	0.25
Deep-drained Grassland	The Netherlands	Best & Jacobs, 1997	0.072	0.06
Deep-drained Grassland	UK	McNamara, 2013	0.580	0.04
Dee-drained Grassland	Russia	Sirin *et al.*, 2012	0.450	0.04
Deep-drained Grassland	Russia	Chistotin *et al.*, 2006	1.989	0.04
Deep-drained Grassland	USA	Teh *et al.*, 2011	1.704	0.05
Shallow-drained Grassland	The Netherlands	Vermaat *et al.*, 2011	0.592	0.25
Shallow-drained Grassland	The Netherlands	Best & Jacobs, 1997	0.345	0.06
Shallow-drained Grassland	The Netherlands	van den Pol-van Dasselaar *et al.*, 1999*a*, *b*, *c*	0.085	0.25
Shallow-drained Grassland	The Netherlands	Hendriks *et al.*, 2007, 2010	0.375	0.10
Drained treed bog	Canada	Roulet & Moore, 1995	0.114	0.03
Drained treed fen	Finland	Minkkinen & Laine, 2006	0.783	0.03
Drained afforested fen	Russia	Sirin *et al.*, 2012	0.139	0.02
Drained afforested fen	Russia	Glagolev *et al.*, 2008	0.088	0.04
Drained treed bog	Canada	Roulet & Moore, 1995	0.028	0.03
Drained afforested bog	Russia	Sirin *et al.*, 2012	0.301	0.01
Drained afforested bog	Russia	Sirin *et al.*, 2012	0.011	0.01
Drained afforested bog	Canada	Roulet & Moore, 1995	0.192	0.03
Drained afforested bog	Sweden	von Arnold *et al.*, 2005*b*	0.013	0.02
Drained afforested bog	Finland	Minkkinen & Laine, 2006	0.053	0.03
Peat extraction site	Finland	Nykänen *et al.*, 1995	0.133	0.02
Peat extraction site	Sweden	Sundh *et al.*, 2000	0.356	0.03
Peat extraction site	Russia	Sirin *et al.*, 2012	1.022	0.04
Peat extraction site	Russia	Chistotin *et al.*, 2006	0.797	0.04
Peat extraction site (inactive)	Finland	Hyvönen *et al.*, 2013	0.011	0.06
Peat extraction (inactive)	Canada	Waddington & Day, 2007	0.110	0.05
Drained blanket bog	UK	Cooper & Evans, 2013	0.070	0.03
Drained tropical peat (abandoned)	Indonesia	Jauhiainen & Silvennoinen, 2012	0.449	0.02
Drained tropical peat (pulpwood plantation)	Indonesia	Jauhiainen & Silvennoinen, 2012	2.939	0.02

Annex 2A.3 Derivation of DOC emission factors

Dissolved organic carbon (DOC) is commonly the largest component of waterborne carbon loss from peatlands and organic soils, with measured fluxes from natural peatlands ranging from 0.04 to 0.63 t C $ha^{-1}yr^{-1}$. In many peatlands, this flux is of comparable magnitude to the rate of long-term carbon accumulation (e.g. Gorham, 1991; Turunen *et al*., 2004), and the size of waterborne carbon flux can therefore determine whether the site is a carbon sink or source (e.g. Billett *et al*., 2004; Rowson *et al*., 2010). If this DOC is subsequently converted to CO_2 via photochemical or biological breakdown processes, this flux will also contribute to overall CO_2 emissions from the organic soil (as an "off-site" emission). This Annex describes the methodology that was used to derive emission factors for DOC losses from drained peatlands and organic soils. At present, it is not considered possible to set reliable emission factor estimates for other forms of waterborne carbon loss, or for the effects of specific land uses and land-use changes (other than drainage) on DOC loss. Methodological requirements to develop these emission factors in the future are described in Appendix 2a.1. The approach is based on Equation 2.5.

Estimation of $DOC_{FLUX-NATURAL}$

Most available published studies of drainage impacts on DOC loss report concentration changes relative to undrained comparison sites, rather than direct (robust) flux measurements. On the other hand, a larger number of studies provide reliable DOC flux estimates from natural, or near-natural, peatland systems. These two data sources (DOC fluxes from natural sites, and DOC changes from drained-natural comparisons) were therefore combined to derive best estimates of the DOC flux from drained sites, following Equation 2.5.

Default values for $DOC_{FLUX-NATURAL}$ were derived from 23 published studies reporting DOC fluxes for 26 sites in total, including natural boreal and temperate raised bogs and fens, temperate blanket bogs and tropical peat swamp forests (Table 2A.2). Most data were derived from catchment-scale studies with natural drainage channels, for which accurate hydrological data are available, and to avoid double-counting of reactive DOC exports from peatlands that are rapidly converted to CH_4 or CO_2 within the ditch network (i.e. on-site emissions). Clear differences in flux were observed according to climate zone, with the lowest fluxes from boreal sites and the highest fluxes from tropical sites, supporting a simple Tier 1 classification system for natural DOC flux estimates based on this classification.

TABLE 2A.2
ANNUAL DOC FLUX ESTIMATES FROM NATURAL OR SEMI-NATURAL PEATLANDS USED TO DERIVE DEFAULT VALUES FOR $DOC_{FLUX-NATURAL}$

Climate zone	Country	Study	DOC flux (t C $ha^{-1}yr^{-1}$)
Boreal	Finland	Juutinen *et al.*, 2013	0.037
Boreal	Canada	Moore *et al.*, 2003	0.043
Boreal	Canada	Koprivnjak & Moore, 1992	0.052
Boreal	Canada	Moore *et al.*, 2003	0.060
Boreal	Finland	Kortelainen *et al.*, 2006	0.060
Boreal	Finland	Jager *et al.*, 2009	0.078
Boreal	Sweden	Ågren *et al.*, 2008	0.099
Boreal	Finland	Rantakari *et al.*, 2010	0.120
Boreal	Sweden	Nilsson *et al.*, 2008	0.130
Boreal	Finland	Kortelainen *et al.*, 2006	0.159
Temperate	Canada	Strack *et al.*, 2008	0.053
Temperate	Canada	Roulet *et al.*, 2007	0.164
Temperate	USA	Urban *et al.*, 1989	0.212
Temperate	USA	Kolka *et al.*, 1999	0.235
Temperate	Canada	Moore *et al.*, 2003	0.290
Temperate	Canada	Clair *et al.*, 2002	0.360
Temperate	UK	Dawson *et al.*, 2004	0.194
Temperate	UK	Dinsmore *et al.*, 2010	0.260
Temperate	UK	Billett *et al.*, 2010	0.234
Temperate	UK	Billett *et al.*, 2010	0.276
Temperate	Ireland	Koehler *et al.*, 2009, 2011	0.140
Temperate	Australia	di Folco & Kirkpatrick, 2011	0.134
Tropical	Indonesia	Baum *et al.*, 2007	0.470
Tropical	Indonesia	Alkhatib *et al.*, 2007	0.549
Tropical	Malaysia	Yule & Gomez, 2009; Zulkifli, 2002	0.632
Tropical	Indonesia	Moore *et al.*, 2013	0.625

Estimation of $\Delta DOC_{DRAINAGE}$

A total of 11 published studies were identified that provided sufficient data to calculate ratios of either DOC concentration or DOC flux between comparable drained and undrained peat sites (Table 2A.3). These included data from boreal and temperate raised bogs and fens, blanket bogs and tropical peats, and drainage for both peat extraction and land-use change to agriculture. There is a reasonable degree of consistency among the studies included; all show an increase in DOC following drainage, with an overall range of 15-118%. Most of the published studies suggest a DOC increase close to the mean (across all studies) of 60%, and there was insufficient evidence to support the use of different Tier 1 $\Delta DOC_{DRAINAGE}$ values for different peat types, climate zones, drainage type or drainage intensity. The use of concentration data to estimate $\Delta DOC_{DRAINAGE}$ does, however, assume no corresponding change in total water flux as a result of drainage, which adds uncertainty to the calculated flux changes. This uncertainty should be relatively small for high-precipitation boreal/temperate bogs, as a large change in water flux could only occur if there is a correspondingly large change in evapotranspiration. For drier bog sites, drainage might be expected to increase water fluxes, therefore amplifying the observed concentration differences between drained and undrained sites (e.g. Strack & Zuback, 2013). However, for fens, which are fed by external groundwater or surface water inputs rather than solely by precipitation, there is greater potential for drainage to lead to fundamental changes in hydrological functioning (e.g. by routing lateral water inputs around the fen rather than through it), thus altering the water flux.

Consequently, although observed DOC concentration changes in drained fens are similar to those from drained bogs (Table 2A.3), the appropriate default value of $\Delta DOC_{DRAINAGE}$ for fens is more uncertain. At Tier 1, it could therefore be assumed that the DOC flux from a drained fen is unchanged from the natural flux (i.e. that $\Delta DOC_{DRAINAGE}$ is equal to zero and that the DOC export is thus equal to $DOC_{FLUX\text{-}NATURAL}$). At Tier 2, it may be possible to develop specific estimates of $\Delta DOC_{DRAINAGE}$ based on paired comparisons between reliable DOC flux measurements for undrained and drained fens, either on a country-specific basis or by pooling studies in different countries. Alternatively, direct measurements of DOC export flux could be used to derive Tier 2 emission factors for DOC emissions from drained fens.

Overall, the available data support a Tier 1 default $\Delta DOC_{DRAINAGE}$ value of 0.60 for drained bogs and tropical organic soils. Given difficulties in quantifying the water budget of drained fens, there is greater uncertainty about the applicable value for $\Delta DOC_{DRAINAGE}$ for this organic soil type. Countries may therefore choose to apply the same Tier 1 default value as for other soil types, or to make the assumption that DOC export does not increase with drainage from fens, i.e. to apply the natural DOC flux value to calculate EF_{DOC}. An exception may also be made where drainage channels are cut into underlying mineral soils, as this has been found to reduce DOC loss (e.g. Moore, 2003).

TABLE 2A.3
DOC CONCENTRATION (ABOVE) OR FLUX (BELOW) COMPARISONS BETWEEN DRAINED AND UNDRAINED ORGANIC SOILS, USED TO DERIVE DEFAULT VALUE FOR $\Delta DOC_{DRAINAGE}$

Organic soil type	Land use	Country	Study	DOC		$\Delta DOC_{DRAINAGE}$ (%)
				Undrained	Drained	
Concentration-based studies (DOC mg l^{-1})						
Boreal bog	Drainage (peat extraction)	Canada	Glatzel *et al*., 2003	60	110	83%
Boreal fen	Drainage	Canada	Strack *et al*., 2008	16	24.29	53%
Boreal fen	Drainage	USA	Kane *et al*., 2010	56	71.7	29%
Boreal fen	Drainage (peat extraction)	Finland	Heikkinen, 1990	17	20	15%
Temperate bog	Drainage	Poland	Banaś & Gos, 2004	48	71	49%
Temperate bog	Drainage (peat extraction)	New Zealand	Moore & Clarkson, 2007	70	108	54%
Temperate bog	Drainage	Czech Republic	Urbanová *et al*., 2011	36	53.9	51%
Temperate fen	Drainage	Czech Republic	Urbanová *et al*., 2011	17	37.5	118%
Temperate blanket bog	Drainage	UK	Wallage *et al*., 2006	28	42.9	55%
Flux-based studies (DOC g m^{-2} yr^{-1})						
Tropical peat	Drainage (sago palm)	Malaysia	Inubushi *et al*., 1998	33	63	91%
Tropical peat	Drainage (agriculture)	Indonesia	Moore *et al*., 2013	62	97	54%

Estimation of $Frac_{DOC-CO2}$

The significance of DOC export in terms of greenhouse gas estimation depends on its ultimate fate, i.e. whether it is returned to the atmosphere as CO_2 (or even CH_4) or deposited in stable forms such as lake or marine sediments. The latter simply represents a translocation of carbon between stable stores, and should therefore not be included in the estimation. The parameter $Frac_{DOC-CO2}$ sets the proportion of DOC exported from organic soils that is ultimately converted to CO_2. While uncertainty remains in the estimation of this parameter, there is growing evidence that fluvial systems process a high proportion of incoming terrestrial carbon, and that much of this is converted to CO_2 (e.g. Algesten *et al*., 2003; Cole *et al*., 2007; Wickland *et al*., 2007; Battin *et al*., 2009). Both Algesten *et al*. (2003) and Jonsson *et al*. (2007) estimated that, within large, lake-influenced catchments in Sweden, around 50% of all terrestrially derived organic carbon was mineralised. Wickland *et al*. (2007) measured 6–15% conversion of pore-water DOC to CO_2, and 10–90% conversion of the vegetation-derived DOC, during one-month dark incubations, while Raymond and Bauer (2001) measured 63% biodegradation of riverine DOC during a one-year dark incubation. Multiple studies showing a strong correlation between lake DOC concentration and dissolved CO_2 concentrations (e.g. Sobek *et al*., 2003; Stutter *et al*., 2011 and references therein) all suggest widespread conversion of DOC to CO_2 in lakes. Dawson *et al*. (2001) estimated that 12–18% of DOC was removed within a 2 km stream reach, Experiments undertaken on light-exposed samples of peat-derived waters (Köhler *et al*., 2002; Jones *et al*., 2013; Worrall *et al*., 2013) consistently show rapid and extensive DOC loss, with averages ranging from 33–75% over periods of up to 10 days. Both Köhler *et al*. (2002) and Jones *et al*. (2013) found that peat-derived DOC was more susceptible to photodegradation than DOC from other water sources, and Köhler *et al*. (2002) found that most of the DOC lost was converted to CO_2 (e.g. Opsahl & Benner, 1998). Jones *et al*. (2013) observed that since much of this degradation occurs within the first 48 hours, this would be sufficient to convert most peat-derived DOC to CO_2 before it enters the sea. Overall, Algesten *et al*. (2003) estimated that 90% of the DOC removal in the large catchments studied was due to mineralisation to CO_2, with only 10% buried in lake sediments. Terrestrially-derived DOC that does reach the sea largely appears to be photochemically or microbially processed in the marine system, mostly within years to decades (Opsahl & Benner, 1997; Bianchi, 2011).

In summary, there is strong evidence that a high proportion of peat-derived DOC is mineralised rapidly in headwaters, that this processing continues at a relatively high rate through rivers and lakes, and that any peat-derived DOC that does reach the sea will nevertheless largely be mineralised in the marine ecosystem. These observations support the use of a high value for $Frac_{DOC-CO2}$. Taking the ratio of mineralisation to sediment burial obtained by Algesten *et al*. (2003), and assuming that a similar ratio applies to any DOC exported to the ocean, would suggest that around 90% of peat-derived DOC is eventually converted to CO_2. On this basis, a Tier 1 default value of 0.9 is proposed, with an uncertainty range of 0.8–1.0 to reflect uncertainties in the proportion of DOC returned to burial in lake or marine sediments.

There is some evidence that controlled burning (for moorland management) also increases DOC losses (e.g. Yallop *et al*., 2010; di Folco & Kirkpatrick, 2011), although other experimental studies have shown no effect (e.g. Ward *et al*., 2007; Worrall *et al*., 2007). A precautionary estimate is that managed burning may increase mean DOC loss by 20–50%, but further work is required to resolve uncertainties on this issue (Holden *et al*., 2012). Grazing levels on semi-natural vegetation have not been shown to affect DOC loss (Ward *et al*., 2007; Worrall *et al*., 2007), and data on the effects of more intensive agricultural (Grassland and Cropland) management on DOC loss are currently insufficient to estimate an emission factor. Generic values for the effects of drainage therefore may be used.

Annex 2A.4 Derivation of CO_2-C and non-CO_2 emission factors for emissions from burning of drained inland organic soils from the scientific literature in Tables 2.6 and 2.7

CO_2 emission factors for fires on drained organic soils were obtained by consideration of the available scientific literature. The data presented in Tables 2.6 and 2.7 provide default values for the mass of available fuel and emission factors.

The data in Table 2.6 were obtained using a variety of approaches to calculate the mass of fuel combusted. It should be noted that there are only a limited number of publications providing ground- or laboratory-based data on the depth (i.e. volume) of soil organic material consumed. Quantitative estimation of depth of burn as well as organic soil characteristics (i.e. bulk density and carbon content) are not easy to determine in the field and so information on these key parameters is often based on theoretical assumptions or on limited ground measurements. This knowledge gap contributes considerably to overall uncertainties related to emissions from fires on organic soils because it is difficult to accurately assess the amount of fuel that is consumed. Field data on depth of burn are available from a number of studies of fires on organic soils in northern forests and peatlands in North America, Europe and Asia (e.g. Zoltai *et al.*, 1998; Turetsky & Wieder, 2001; Page *et al.*, 2002; Benscoter & Wieder, 2003; Ballhorn *et al.*, 2009; de Groot *et al.*, 2009; Turetsky *et al.*, 2011*a*), while in other cases, data have been extrapolated from previous studies.

Obtaining accurate field data on the depth of combustion on organic soils is problematic since there is usually a lack of reference data. Turetsky and Wieder (2001) developed a method for field assessment that considered the rooting depth of trees, while other studies have used comparison of adjacent unburnt sites to quantify combustion depth (e.g. Kasischke, 2000; Page *et al.*, 2002; de Groot *et al.*, 2009; Turetsky *et al.*, 2011*a*) or measurement of fuel loads before and after experimental fires (e.g. Usup *et al.*, 2004). The use of LiDAR remote sensing has also been applied in one study (Ballhorn *et al.*, 2009).

Nearly all the data presented in Table 2.6 for boreal and temperate zones are actually from the boreal zone, with only one study in the temperate zone (Poulter *et al.*, 2006) and two studies in the tropical zone (Page *et al.*, 2002; Ballhorn *et al.*, 2009). Most studies are of wildfires (i.e. unwanted and unplanned fires ignited other than by prescription (e.g. by lightning or as a result of human activities, including escaped prescribed fires as well as those started through negligence or by arson) and are for fires on undrained peatland organic soils. Only Turetsky *et al.* (2011*b*) provide depth-of-burn data for a wildfire on a drained boreal organic soil. In addition, there are no data for organic soil losses associated with prescribed fires in the boreal/temperate zone but some studies suggest that DOC increases following fire (see also Annex 2A.2). Most prescribed (i.e. managed) fires on the vegetation of organic soils probably result in either no or only minimal ignition loss of soil carbon.

Fuel moisture content, depth of water table and burn history will all determine the extent of organic soil combustion during a prescribed fire but the scale of loss will often depend on the skill and experience of the fire manager. In some parts of the temperate zone, prescribed rotational burning of vegetation on organic soils is a long-established land-management practice. In the UK, it is carried out on about 18% of peatlands, predominantly in the uplands (Marsden & Ebmeier, 2012), with the aim of removing older, less productive vegetation and encouraging new growth for livestock grazing and cover for game birds (Worrall *et al.*, 2010). In North America, prescribed burning of vegetation on organic soils is also practised, with a range of benefits including the reduction of wildfire hazards, improvement of wildlife habitats and restoration of ecosystem diversity and health (e.g. Christensen, 1977). Typically, prescribed burning will be carried out when fuel moisture is high enough to prevent combustion of the organic soil but low enough to carry a surface fire, thus reducing the risk of soil ignition. Shifts in climate have narrowed the window of opportunity for prescribed burning and changes in weather patterns have resulted in unexpected drying of peatlands during ongoing prescription burns. Some local fire managers have recognised this shift, but unfortunately this is a minimally studied area and little information exists on the scale of emissions arising from the combustion of organic soils during prescription burns. At Tier 1, it is assumed that there is either no or very little combustive loss of soil organic matter during prescribed fires on organic soils.

The average depth of burn of tropical organic soils has not been explored in a consistent way that representatively covers the different geographical regions, vegetation types, or fire types (i.e. wild vs. prescribed fires). There have been a limited number of field measurements of depth of burn and estimates of organic soil combustion losses. These have used either direct field measurements (e.g. Page *et al.*, 2002; Usup *et al.*, 2004) or a combination of field measurements and LiDAR data (e.g. Ballhorn *et al.*, 2009). There are only three studies of wildfires on drained organic soils and none in undrained organic soils, although other studies have demonstrated that, when in an intact condition, tropical peat swamp forest is at very low risk of fire (e.g. Page *et al.*, 2002).

There have been a limited number of studies investigating depth of burn on drained organic soils under agricultural management (e.g. Saharjo & Munoz, 2005). Prescribed agricultural burning is undertaken on both a small and a large scale to improve soil fertility and/or to remove forest or crop residues during land preparation activities. For example, traditional "*sonor*" rice cultivation on shallow organic soils involves regular burning of crop residues along with the soil surface to enhance soil fertility. In addition to field measurements, there have been limited laboratory-based burn tests aimed at establishing environmental controls on depth of organic soil combustion (e.g. Benscoter *et al*., 2011). While more field and laboratory experiments to determine fuel consumption during fires on organic soils are needed (French *et al*., 2004), there is also a need for improved remote sensing methods to aid burn severity mapping in peatlands (defined as the magnitude of ecological changes between pre- and post-fire conditions), which can provide an indication of the likely depth of burn. Burn severity is not easy to either investigate or quantify but there have been a limited number of studies using spectral indices to discriminate different levels of burn severity in boreal and temperate forests (e.g. van Wagtendonk *et al*., 2004; Epting *et al*., 2005; Hall *et al*., 2008) but only one study to date of tropical organic soils (Hoscilo *et al*., 2013). Even regionally developed consumption models can have large uncertainties with respect to organic soil consumption. The development of robust methodologies to assess burn severity and total organic soil consumption in wetlands would enable more accurate quantification of carbon emissions from both above-ground and below-ground fires for reporting at higher tiers.

Accurate assessment of the volume of organic soil combusted during a fire will only be feasible at Tier 2 and Tier 3, while at Tier 1 some simplifying assumptions are required.

Appendix 2a.1 Estimation of Particulate Organic Carbon (POC) and Dissolved Inorganic Carbon (DIC) loss from peatlands and drained organic soils: Basis for future methodological development

This Appendix provides a basis for future methodological development rather than complete guidance.

Particulate Organic Carbon

Particulate organic carbon (POC) is generally a negligible component of the carbon balance of natural peatlands and organic soils. However, disturbance of organic soils through land-use change, including drainage (which can include the dredging of peat from drains and canals), burning (managed burning and wildfire), conversion to arable land and peat extraction, can all result in high rates of POC loss via waterborne erosion and also wind erosion. In actively eroding blanket bogs, POC losses in excess of 100 g C m^{-2} yr^{-1} may represent the dominant form of soil carbon loss (e.g. Pawson *et al*., 2008; Worrall *et al*., 2011).

Available data suggest that the key determinant of POC loss is the proportion of the total area occupied by exposed (bare) peat, according to Equation 2A.1. The bare peat area, $PEAT_{BARE}$, would include unvegetated drainage ditches, erosion gullies, peat extraction surfaces and areas of the soil surface exposed by burning, intensive grazing or the deposition of peat dredged from drainage channels onto the land surface. For Cropland, some estimation of the annual average proportion of the organic soil surface exposed over the full crop rotation would be required. Data from eroding UK blanket bogs suggest that waterborne POC exports can be reasonably well predicted based on a POC flux from bare peat surfaces ($POC_{FLUX\_BAREPEAT}$) of around 4 t C $ha^{-1}yr^{-1}$ (Goulsbra *et al*., 2013). Further work is required to establish whether different values would be applicable to other soil types, land-use types and climate regimes (in particular whether it is dependent on precipitation amount or intensity). At present, there are few data on which to base an estimate of airborne POC loss, and further work is required to quantify this loss term, which may be large in peat extraction and Cropland sites.

Finally, there is limited information currently available from which to derive a value for the proportion of POC ultimately converted to CO_2 ($Frac_{POC\text{-}CO2}$). Unlike DOC, a substantial proportion of POC is mobilised from organic soils through physical erosion processes, and its reactivity in fluvial systems is uncertain. Some studies have shown fairly high rates of POC turnover in river and estuarine systems (e.g. Sinsabaugh & Findlay, 1995), and POC redeposited on floodplains may be subject to moderate rates of oxidation (Goulsbra *et al*., 2013). However, it is likely that a significant proportion of waterborne POC loss from organic soils may simply be transferred to lake or coastal sediments, redeposited on floodplains or transported to other land areas via aeolian transport, rather than converted to CO_2. Further research is therefore needed to establish realistic ranges for $Frac_{POC\text{-}CO_2}$ in different systems.

EQUATION 2A.1
CALCULATION OF POC EXPORT FROM DRAINED ORGANIC SOILS

$$EF_{POC} = POC_{FLUX\_BAREPEAT} \bullet PEAT_{BARE} \bullet Frac_{POC-CO_2}$$

Where:

EF_{POC} = POC emission factor, t C $ha^{-1}yr^{-1}$

$POC_{FLUX\_BAREPEAT}$ = Flux of POC from a bare peat surface, t C $ha^{-1}yr^{-1}$

$PEAT_{BARE}$ = Proportion of the ground surface occupied by exposed peat

$Frac_{POC\text{-}CO2}$ = Conversion factor for the fraction of POC converted to CO_2 following export from site

Dissolved Inorganic Carbon

Waterborne carbon fluxes from organic soils, comprising bicarbonate ion (HCO_3^-), carbonate ions (CO_3^{2-}) and free CO_2, are collectively termed dissolved inorganic carbon (DIC). These different carbon species exist in equilibrium, depending primarily on the pH of the water. In water-draining low-pH organic soils (i.e. bogs), almost all DIC is present as CO_2. Most of this CO_2 derives from autotrophic and heterotrophic respiration within organic soils, and is transferred laterally from soils into drainage waters, where it is consistently present at concentrations well in excess of atmospheric CO_2 concentrations. This supersaturated CO_2 will be emitted (“evaded” or “degassed”) to the atmosphere, typically within a few kilometres of its source (e.g. Hope *et al*., 2001). Limited measurements of CO_2 evasion from natural peatlands suggest that this emission is a quantitatively significant component of the overall carbon budget. For example, Dinsmore *et al*. (2010) recorded a DIC flux of 0.12–0.16 t C $ha^{-1}yr^{-1}$ at a Scottish peatland catchment, of which over 90% was evaded to the atmosphere within the first 5 km of stream length. Although this may be considered an "on-site" emission, in practice it will not be measured as part of the terrestrial CO_2 emission using chamber-based methods, and is unlikely to be captured by eddy covariance methods. Consequently, direct measurements of CO_2 emissions from water bodies draining organic soils (e.g. using floating chambers or gas transfer coefficients linked to measurements of dissolved CO_2 within the water column) are likely to be required in order to obtain reliable estimates of this component of the carbon flux. Currently, only a few such measurements are available for undrained organic soils (e.g. Hope *et al.*, 2001; Billett & Moore, 2008; Dinsmore *et al.*, 2009, 2010; Wallin *et al.*, 2011). For drained organic soils, insufficient data are currently available to permit default emission factors to be developed. Further measurements of CO_2 evasion for a range of climate zones, soil types, land-use classes and drainage systems are therefore required to support future methodological development in this area. Care is required to avoid double-counting of CO_2 emissions associated with mineralisation of DOC within downstream water bodies, as opposed to direct degassing of CO_2 released from the organic soil into the water body.

As noted above, other components of the DIC flux can be considered minor for bogs, due to their low pH. This is not the case for fens, which have a higher pH, so that HCO_3^- and CO_3^{2-} may form significant components of total DIC export. However, a high proportion of this flux may derive from weathering processes external to the organic soil (i.e. in groundwater or river water inputs to the fen) and this geogenic flux cannot be considered a part of the internal carbon budget of the organic soil (Fiedler *et al.*, 2008). On the other hand, autotrophic and heterotrophic respiration processes may also generate dissolved CO_2, which can then dissociate to form HCO_3^- and CO_3^{2-} in alkaline waters. This flux *does* form a component of the organic soil carbon balance, but further work is needed in order to: 1) quantify this flux (particularly for drained organic soils); 2) differentiate this biogenic DIC from geogenic DIC (e.g. using isotopic methods); and 3) determine the proportion of DIC exported from organic soils that is ultimately returned to the atmosphere as CO_2, rather than sequestered into sediments, such as marine carbonate deposits.

Finally, available data consistently suggest that, other than emissions from drainage ditches (see Section 2.2.2.1), on- or off-site emissions of dissolved CH_4 from water bodies represent a negligible component of the total carbon and greenhouse gas budget of organic soils (e.g. Hope *et al.*, 2001; Dinsmore *et al.*, 2010; Billett & Harvey, 2013).

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